Final Report for
Advanced Microwave Frequency
Sources and Filters based on
Superconducting Photonic
Band Gap Structures

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INTRODUCTION

The concept of a photonic band gap is very similar in character to a number of other physical systems, most notably energy gaps in semiconductor band structures. The essential ingredients are a wave phenomenon and a regular lattice of wave scatters. In the case of semiconductors, the charged electrons are in a regular crystalline lattice of atoms (positive charge centers). With the proper electron density and periodicity of the lattice, one finds forbidden energy bands within which charges can not exist.

In a similar way, one may arrange for a periodic structure of dielectrics. The dielectric constants and the lattice can be chosen so as to create forbidden bands, or frequency ranges, in which electromagnetic waves cannot propagate, i.e., a photonic band gap [1,2].

To draw the analogy further, consider the effect of doping the semiconductor lattice with an impurity atom. Done properly (i.e., with the right impurity atom), one can create an energy state that exists within the forbidden energy band. In the same way, one may create an “impurity” or “defect” state in the photonic band gap by altering the size or dielectric constant of one of the lattice sites. An energy state will be localized about this impurity site, meaning the mode does not propagate through the lattice [3,4].

Once a “defect” mode is excited or energized, it will dissipate only in a few ways. If these avenues are somehow minimized, the excited mode will have a long lifetime and a very precise frequency, i.e., the defect mode in the photonic band gap is essentially a high Q “cavity”. It is this aspect of the photonic band gap that has attracted attention, as this provides a means of creating an ultrahigh precision frequency source for real world applications.

In principle, the concept of a photonic band gap can be applied in one, two or three dimensional dielectric lattices [5-7]. Full three dimensional lattices can, and have been constructed. However, they are in practice very difficult to make, and the confinement of a defect mode depends upon the existence of a photonic band gap in all three dimensions. Two dimensional lattice, bounded above and below by conductive plates are much easier to realize in practice, and the theoretical calculations, while still difficult, are still easier to perform. It is the two-dimensional Photonic Band Gap structure that we have targeted.

The concepts and theory of PBG are completely scaleable to any desired operating frequency. Thus it is relatively easy to design a device for operation at any target frequency, and the same device can be operated over a small frequency range within the PBG by varying the size of the defect that creates the defect mode. The size of the device is of course related to the wavelength of the defect mode. This sets the scale, and as we will discuss momentarily, the actual PBG device size will be roughly 10 times the free space wavelength. For this work, we chose to operate in the 35 GHz regime (K band), and the resultant device size was a little over 4 inches in diameter.

The energy loss mechanisms for a defect mode in a photonic band gap can be separated into three channels. One, the dielectric medium can be lossy. This can
be characterized by a material property called the “loss tangent”. In choosing the
dielectric medium to be used for the photonic band gap structure, one should select
a material with a low loss tangent. Secondly, the defect mode, while localized, can
extend to edge of the physical lattice where the mode can drive a propagating
mode and allow energy to escape. This loss mechanism is referred to as
confinement loss. The solution of this problem is simply to make the physical lattice
large enough that the characteristic size of the mode, called the localization length,
is many time smaller than the actual size of the lattice. For our purposes here, the
size of the structure was about 30 lattice constants in diameter. Lastly, the bounding
conductive surfaces above and below the two-dimensional structure have surface
resistance which causes resistive heating, another loss mechanism. The solution to
this problem is to select a highly conductive material (low surface resistance).
Superconductors are obvious choices here, and will be discussed further shortly.
More detailed discussions of losses, both theoretical and actual, are of course
described later in this report.
In this work, we have selected sapphire as the dielectric. It has a reasonably high
dielectric constant (> 11) and can be produced with very low loss tangent. Through
mathematical modeling, we were able to select a sufficiently large lattice size to
safely reduce the confinement losses to negligible levels. Together, the dielectric
and confinement losses were sufficiently small that the dominant loss mechanism
was the surface resistance of the conductive surfaces. Low temperature
superconductors (LTS), such as niobium, are the best choices for the
superconducting walls. However, LTS materials require expensive refrigeration
methods, either liquid Helium or advanced cryocoolers, to reach a few degrees
Kelvin, and are generally more difficult to handle and maintain. High temperature
superconductors offer a more economical alternative by only requiring cooling to
near 77K (such as with relatively inexpensive liquid nitrogen). The handling and
maintenance requirements would be much easier. For real world applications, this
is usually necessary for any widespread use.
There are other properties of the PBG device that are attractive. The PBG defect
mode is a single mode (one mode per band). Higher modes are easily separated
and eliminated. The PBG device can easily be ruggedized, an important feature for
field deployment. The device as built is actually quite solid and rugged, although no
particular design effort was expended in this area. The PBG device is naturally a
solid sandwich of materials. The solid construction is also important in reducing
effects of microphonics on the mode frequency.
To actually achieve an operating device, there were a number of problems to be
addressed. A number of theoretical questions remained following the Phase I effort.
Among these were to investigate other modes in the PBG structure called hybrid
modes. The actual device design (including lattice type, spacing, and thickness)
needed to be confirmed, and we needed a more detailed understanding of the
expected device characteristics.
Sapphire is an extremely hard material with a hardness of 9. The lattice design
called for a square lattice of over 1500 holes in a 4 inch diameter disk. The web
thickness between holes would only be about 0.008 inches. Choosing a practical
method of producing such a lattice, maintaining hole size, spacing and registration while minimizing hole taper and chipping, was clearly a challenge. It was decided to produce a smaller 15 x 15 lattice in sapphire initially to investigate and verify a number of the PBG characteristics before investing in the full scale lattice production.

Coupling microwave energy into the defect mode was another challenge. Operating at 35 GHz is relatively difficult because mismatches at transitions in the microwave structures can easily generate large VSWR’s, or reflections. Adapting existing K band microwave technology into this application needed to be done carefully, and was complicated by the fact that it would also need to be done at cryogenic temperatures and would require transition into vacuum.

Fortunately, the PBG device can easily operate at room temperature, in air, and using copper supporting plates. This allowed us to separately address many of the problems we faced. The PBG device characteristics could be verified separately from issues related to the microwave handling, coupling and cryogenic design. The coupling design could be optimized initially at room temperature by a series of relatively quick turn around trial and error iterations. This experience would govern later adjustments at cryogenic temperatures as well.

Furthermore, the PBG device will function with Cu supporting plates at liquid nitrogen or liquid helium temperatures as well. This allows us to track the device operation due to thermal property changes without the complication of superconducting transitions, or the details of the HTS film substrate design. Thus we were able to reach moderately high Q levels easily, and confirm the cryogenic, microwave, and instrumentation performance. The subsequent transitions to first LTS and then HTS walls could be undertaken with a greater degree of confidence in the other fundamental operations at work.

The most basic characterization, and the most important performance measure of the device that was determined at each stage of the development, was the Q of the device. Of course the ultimate objective was to build the PBG device into an amplifier circuit to make a stable frequency source. A low insertion loss device is therefore necessary as well. Coupling, and the ability to adjust the degree of microwave coupling is important in this respect as well.

The oscillator circuit was accomplished using custom built microwave amplifiers. With sufficient gain, and the proper phase shift around the circuit, a stable oscillator can be formed using the PBG structure as the frequency source. The PBG element has two ports, one on each side. They are located several lattice sites from the defect and couple into the tails of the defect mode energy distribution. This arrangement helps to minimize the effect of the port entry into the PBG structure by having neither port at the center or “peak” of the mode. Sufficient coupling is still achieved.

To measure the Q of the device, a high speed switch was incorporated into the feedback circuit. By first energizing the PBG defect mode, and then shutting the switch, the decay of the energy in the mode can be monitored to provide a decay time and hence a Q measurement. This methodology is needed for measuring large Q’s in excess of $10^6$. 
LTS supporting plates, made of niobium, were produced and used in a PBG device. The Nb surface was machined and subsequently mechanically polished. A loaded Q in excess of $10^6$ was measured. More careful control of the surface preparation could probably easily improved the Q significantly. All the same, this value was significantly higher than what would be expected with HTS, and served to indicate that the device would not be limited by losses other than surface resistance, and that the measurement instrumentation was adequate to the job.

Incorporating HTS surface into the structure poses additional problems. The HTS must be first deposited onto an appropriate substrate, LaO$_2$ or sapphire. Also, provisions must be made for penetrating the coupling ports through the HTS substrate and film, and for minimizing microwave leaks into the HTS substrate (LaO has a dielectric constant of 25). The HTS film/substrate must be supported by some superstructure which holds the entire device together.

Producing high quality large area films of 4 inch diameter is difficult. For the HTS portion of this project, 2 inch diameter films were used. These were inset into Cu plates, so that a portion of the defect mode would be bounded by Cu, and a portion by the 2 inch HTS films.

A pair of HTS films were produced by Conductus in Sunnyvale, CA. No evidence of defect modes were found, and later inductive testing of the films failed to show superconductivity. An additional pair of films were produced by Neocera in Maryland. Similarly, no evidence of the defect modes was found. These results have been discussed with both HTS manufacturers, and further technical advisement is awaited.

The technical objectives of the Phase 2 research were the following:

1. **Finalize the design of the K-band PBG resonator. Undertake additional theoretical investigation of hybrid mode** - The following parameters of the two-dimensional dielectric square lattice were selected: lattice material and crystal orientation - rhombohedral sapphire, c-axis (with dielectric constant of 11.56 @ 300 K) perpendicular to 2-D square lattice; PBG lattice diameter - 4"; lattice spacing - 0.084"; hole diameter - 0.076"; lattice thickness - 0.080" (based on investigation of hybrid mode, the lowest hybrid band for the above lattice parameter lies in a frequency range above 60 GHz); PBG center frequency - 35.11 GHz; band gap - 4.4 GHz.

2. **Assemble a millimeter-wave test stand** - A millimeter-wave test stand with computer controlled data acquisition system for transmission and reflection measurements was built.

3. **Build 15x15 dielectric square lattice, and fulfill preliminary evaluation of the PBG and defect modes** - Preliminary test with 15x15 sapphire squire lattice showed the existence of band gap in the K-band and resonance mode associated with a defect in the band gap.

4. **Based on calculated parameters fabricate PBG dielectric structure and defects, build the K-band PBG resonator with copper supporting plates. Prove the existence of the band gap and the defect state in the PBG. Optimize coupling ports and the PBG resonator and at room temperature for the highest Q** - For the fabricated PBG structures
there exists a band gap with lower edge starting at approximately 35 GHz and reaching 39.5 GHz or higher, the upper limit of our microwave source. For the K-band PBG resonator with copper supporting plates at room temperature, there were two resonance modes (at around 35 and 38 GHz) associated with each defect. The defect mode frequency increased with defect size for both resonances. It was shown that for the available defect sizes the higher frequency mode was near the middle of the band gap, and, therefore, was the localized high Q mode with the energy density distribution as is predicted in the theoretical calculations. The Q was in the range of 900 ~ 2000. Antenna-type coupling ports were used to couple microwave energy into the PBG resonator - standard size glass beads manufactured by Wiltron were utilized; the coupling strength could be changed by varying the separation between the coupling port and the defect. It was desired to keep the insertion losses of the structure under about 10 dB while simultaneously avoiding strong perturbation due to the coupling (a slightly undercoupled operative mode was targeted). Operating at cryogenic temperatures it was determined that a near optimal separation between coupling ports of 6 lattice spaces in <01> direction of dielectric periodic structure was needed.

5. **Design and build the cryogenic system for operating at liquid helium temperatures.** - The cryogenic system for operating at liquid helium temperatures was built. This system by itself is sufficiently ubiquitous that it can be used as a platform for a variety of microwave experiments, both transmission and reflection.

6. **Evaluate the PBG resonator with copper plates at cryogenic temperatures. Design and build niobium superconducting supporting plates. Test and optimize the PBG resonator with superconducting plates. Revise PBG structure, defect geometry, and construction.** - The observed Q for PBG resonator with copper plates at 77 K was in the range of 4000 ~ 12000. The PBG resonator with superconducting niobium plates operating at 4.2 K was constructed, and the loaded Q values of 1.1x10^6 order magnitude were observed. The Q was evaluated through the time constant of energy decay stored in the resonator. The coax microwave energy was somewhat undercoupled to defect mode, it is expected that the unloaded Q should be in the 1.1x10^6 ~ 2.2x10^6 range. All three mechanisms of energy dissipation in the PBG (dielectric losses, confinement losses, and losses due to the surface resistance of supporting plates) were investigated. The main energy dissipation mechanism in the PBG resonator with superconducting niobium plates is due to surface resistance of the plates. Better machining in combination with the surface treatments such as chemical polishing, electropolishing, anodic oxidation (and then stripping the oxide), ultrahigh vacuum annealing can result in substantial Q increase.

7. **Build and test the closed-circuit oscillator based on the PBG resonator.** - The closed-circuit oscillators based on the PBG resonators
were constructed. A very stable single frequency corresponding to the introduced defect mode could be excited in the oscillator circuit. The oscillator's Q had the same magnitude as the corresponding resonator.

8. **Design and build the HTS supporting plates. Test and optimize the PBG resonator with HTS supporting plates. Pattern HTS wafers for optimum input/output coupling. Revise PBG structure, defect geometry, and construction. Construct additional PBG resonators.** - A PBG resonator with HTS supporting plates was designed and built as follows: a YBCO film was deposited on a sapphire or LaAlO3 substrate of 2.0" diameter, and then inserted into the copper plate. To demonstrate that the defect mode exists in the resonator with composed (discontinuous) surfaces, 2.0" diameter copper plates (instead of YBCO film on a substrate) were inserted into the copper supporting plates and tested. The first pair of YBCO films on sapphire substrates was produced by Conductus (Sunnyvale). The second pair of YBCO films on LaAlO3 substrates was delivered by Neocera (Maryland). In both cases we could not observe a defect mode with YBCO composed supporting plates.

9. **Seek and evaluate potential applications of superconducting PBG oscillator-resonators. Perform cost analysis for manufacture and sales.** - There is a demand for high Q low phase noise microwave resonators-oscillators. The PBG resonator has already shown Q values comparable to the contemporary state-of-art dielectric cavity resonators. The advantages of the PBG resonator to dielectric cavity resonators were identified as the following: while dielectric cavity resonators are sensitive to the microscopic properties of the dielectrics such as temperature stability, vibration, etc., PBG resonators are sensitive to the macroscopic properties of a periodic dielectric structure (PBG structure). The PBG structure is quite rigid mechanically. The PBG resonator is a true single frequency resonator, while all possible harmonics are present in the dielectric cavity resonators. The cost analysis for the PBG filter-oscillator manufacture showed that it can be priced competitively.

The Chapters that follow illustrate and describe in greater detail the efforts towards these objectives.
1. PHOTONIC BAND GAP AND DEFECT MODE FOR TWO DIMENSIONAL STRUCTURE

1.1 THEORETICAL DESCRIPTION OF TM MODE.

1.1.1 OPTIMIZATION OF THE BAND GAP

The two-dimensional system which is presented schematically in Figure 1.1.1 was under investigation. The separation between bounding conducting or superconducting surfaces is chosen so that it cuts off higher order frequencies, allowing only two-dimensional modes, those in which the field does not vary as a function of the axial coordinate. This greatly simplifies the numerical analysis, since the behavior of these modes is simpler to model and understand. It is also easier to fabricate this structure, and it might be easier to achieve the electromagnetic wave localization within the two-dimensional structure. Due to the nature of the axial confinement, only TM modes, in which the electric field is parallel to the Z axis and the magnetic field lies in the X-Y plane, satisfy the requirement of being two-dimensional. For this case, Maxwell’s equations reduce to a single scalar wave equation, which can be written in Cartesian coordinates as

\[
\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = -\epsilon(x, y) \frac{\omega^2}{c^2} E
\]  

(1.1.1)

where the dielectric function \(\epsilon(x,y)\) is periodic in \(x\) and \(y\), and uniform in \(z\). Expanding both the dielectric function and the field in plane waves, we can rewrite Eq. (1.1.1) as

\[
\frac{c^2}{\omega^2} u^\xi = \sum_{\|\kappa\| \leq 1} \frac{(\delta_{G,G'} + \chi_{G+G'})}{\sqrt{(\kappa + G) \times (\kappa + G)} \times \sqrt{(\kappa + G') \times (\kappa + G')}} u^\xi_{G'}
\]  

(1.1.2)

where \(\kappa\) is a Bloch vector lying within the first Brillouin zone, and \(G\) and \(G'\) are reciprocal lattice vectors. We have written Eq. (1.1.2) as a finite rank eigenvalue
equation, with size determined by a plane wave cutoff vector $G_c$. The details of the spatial dielectric function are contained in

$$\chi(x) = \frac{[\varepsilon(x) - 1]}{4\pi},$$

from which can be found the Fourier space coefficients

$$\chi_G = \frac{1}{a_{\text{unit cell}}} \int \chi(x)e^{iG\cdot x}dA \quad (1.1.3)$$

$a_{\text{c}}$ is the area of a unit cell, and $x$ is a two-dimensional position vector. The integral in Eq. (1.1.3) can either be done analytically, if the geometry is simple enough, or numerically (e.g., using an FFT) for more complicated structures. Equation (1.1.2) is generally solved to find the frequencies of the lowest bands of interest; this is known as the Plane Wave (PW) method. Convergence is improved as more plane waves are included in the calculation; the standard criteria for convergence is that the band structure in the range of interest remains stable as more and more plane waves are added, although care must be taken to avoid regions of quasi-stability.

Finally, the eigenfields can be determined from

$$E_\kappa = \sum_G u_G^xe^{i(k+G)} \quad (1.1.4)$$

Note that solving Eq. (1.1.2) produces information on the band-gaps, but not on the defect modes of ultimate interest. However, Eq. (1.1.2) can also be used to compute the complex photonic band structure, which is determined by allowing $k$ to have complex components. When $k$ has complex components, however, Eq. (1.1.2) is no longer Hermitian, and the eigenfrequencies no longer are necessarily real-valued; in this situation, we select all solutions which do have purely real frequencies as composing the complex band structure.

The complex band structure can be used to find information about the rate of decay of evanescent modes occurring at frequencies corresponding to the band gap frequencies. These modes, forbidden in infinitely periodic structures, are allowed in terminated photonic lattices and lattices containing defects. A complex band structure for the final photonic lattice geometry was carried out, yielding a decay length of 2.4 mm along the [10] symmetry direction of the lattice, at the center band gap frequency. This information was used to estimate the size of the photonic lattice needed for a given Q, assuming a defect could be created at the center band gap frequency. Since the decay-length
varies as a function of direction in the lattice, and since the decay-length quoted above represents the maximum, the estimate of 100 mm for total photonic lattice size was conservative.

1.1.2 FINITE DIFFERENCE NUMERICAL METHOD FOR THE DEFECT MODE CALCULATION

The PW method described above fails, due to convergence difficulties, when more elaborate structures are simulated. Due to the cost of obtaining the high quality dielectric inverse lattice, it was essential to compute the parameters which would place a defect in the band gap, before actually fabricating the lattice. For this reason, we applied a Finite Difference (FD) based numerical method, which proved quite successful in predicting the defect parameters which would result in a defect mode at the frequency of interest. The finite difference version of the wave equation has the form

\[
E_{i+1,j} = \left[ 4 - \frac{\omega^2 l^2}{c^2} \varepsilon_{i,j} \right] E_{i,j} - E_{i+1,j} + E_{i,j+1} - E_{i-1,j} \quad (1.1.5)
\]

Eq (1.1.5) can be solved as a standard eigenvalue problem, with periodic or conducting boundary conditions. “i” and “j” index the discretized coordinates, and “l” is the discretization length. To solve for defect modes, we typically simulate a "super-cell" consisting of numerous rows of photonic lattice, containing a defect, and having periodic boundary conditions. For reasonable convergence, the number of discretization points (and hence matrix rank) is usually on the order of tens of thousands; this size matrix would be nearly impossible to solve with standard eigenvalue/eigenvector techniques. However, from the form of Eq (1.1.5) we see that the matrix is actually sparse, and thus specialized techniques can be applied to find the eigenvalues and eigenvectors of the system. The specific algorithm used for these calculations is called "Lanczos Algorithm for Large Symmetric Hermitian Eigenvalue Computations"[8].

Numerous defect calculations were run using the above method, and it was found that a defect mode could in fact be placed in the center of the band gap, localized to the extent that the mode losses would be due to those of dielectric and conductor/superconductor materials, rather than due to leakage out from the periphery of the structure.
Two-Dimensional Photonic Band Gap Structure

Figure 1.1.1
1.2 CALCULATED PARAMETERS FOR TM MODE BAND STRUCTURE AND DEFECT MODE AT AROUND 35 GHz

We initially performed an exhaustive study of numerous photonic lattice geometries and parameters to find a practical configuration which would have a suitably large band gap. We computed band structures for square and triangular dielectric lattices, with various-shaped scatterers; these were done both for dielectric scatterers in air-hosts, and for the case of air scatterers in dielectric hosts. The ratio of scatterer dimension (radius) to lattice spacing, as well as dielectric constant, were varied over a considerable range. These calculations were carried out using the Plane-Wave (PW) method of computation, in which the wave equation is Fourier transformed and solved in reciprocal space. The result of this study was that a significantly large band gap could be found in a dielectric (with $\varepsilon \sim 9$) square lattice with air holes.

In the initial proposal, band structure and defect modes were calculated using the sapphire a-b plane dielectric constant. Sapphire has rhombohedric symmetry. Along its c-axis, it has a dielectric constant of 11.56 at room temperature, and in the a-b plane it has a dielectric constant of 9.39. As we have designed the PBG structure we have now taken the c-axis to be perpendicular to the 2-D plane. And as the TM mode will be the mode of operation, the E-field will also lie in this direction. Thus, we have recalculated the band structures and the defect modes with a dielectric constant of 11.5. This has resulted in no qualitative differences from the earlier calculation (which used 9 as the dielectric constant). There are only slight changes (approx. 10%) in the design dimensions, which due to the increased dielectric constant have decreased the overall lattice spacing $d$ and improved the $a/d$ ratio slightly.

Figure 1.2.1 shows the band structure for design parameters $d=0.213$ cm, $a/d=0.45$ (the hole radii are $a=0.096$ cm). This translates to a lattice spacing of 0.084” and hole diameters of 0.076”, and these were the specifications sent to the sapphire fabricators. With these parameters the expected gap center is at 35.11 GHz, the gap width is 4.44 GHz, or 12.6% of the center frequency.

With these design parameters, one is also interested in the how the gap locally depends upon the lattice spacing $d$, and the hole size through the $a/d$ ratio. These numbers indicate the precision necessary for the sapphire machining, and what kind and size of effects one might expect from small deviations from the quoted specifications. A critical dimension as far as fabricating the PBG dielectric is the thickness of the wall separating two adjacent lattice sites, the web thickness. The above specifications leave a web thickness of 0.008”. Breakout of webs is of concern both during fabrication, and due to mechanical stress during device assembly and use.

Figures 1.2.2 through 1.2.5 show how the gap center frequency and the gap width depend upon the lattice spacing, the hole size, and the dielectric constant. In Figure
1.2.2 we assume a lattice spacing of 0.084" in c-axis sapphire ($\varepsilon = 11.5$). The top graph is provided as a convenient guide to the relationship between the a/d ratio, the resulting web thickness, and the gap expressed as a percentage of the fundamental frequency ($f_0 = 35$ GHz). It is necessary to maintain a gap of at least 8% in order to insure a sufficiently short localization length. As will be seen shortly, the confinement losses are exponentially related to this localization length. In the lower plot is shown the relationship of the gap, expressed in bandwidth, to the a/d ratio. From these plots it is evident that a relatively high tolerance is needed. Our initial aim was to obtain a 12% gap, which requires a web thickness of about 0.008". One can see from this figure that 0.003" error can reduce the gap to 8%. It is difficult to predict what the effect will be from a combination of errors in the hole diameters and errors in the hole positions. In conversations with fabricators familiar with ultrasonic drilling, one can expect tapers in the hole diameters of up to 0.001". Thus it was a real concern how accurately the PBG structure could be fabricated, at least in the initial phase, and what the effects of various errors would be.

The upper plot in figure 1.2.3 shows how the center gap frequency depends on the hole diameter, while the lower shows the relationship between the gap bandwidth and the hole diameter, again assuming a lattice spacing of 0.084". We consider that the exact frequency is of less concern for two reasons. First, for proof of concept the precise mode frequency is not critical, and secondly, by adjusting the defect hole size we have some latitude to adjust the resonant frequency. Nonetheless, it will still be necessary to operate the device near the center of the gap, and it is apparent from this figure that a roughly 0.002" error in hole diameter will shift the center frequency by roughly 1 GHz.

Also of concern is the effect of changes in the dielectric constant. We expect to operate both at room temperature and at cryogenic temperatures. Sapphire has a c-axis dielectric constant of 11.56 at room temperature, 11.43 at 200 K and 11.36 at 77 K. Shown in figure 1.2.4 are the dependencies of the center frequency and the band gap on the dielectric constant in the neighborhood of 11.5. A shift in the dielectric constant by 0.2 causes only a 0.28 GHz change in the center frequency, and a 0.1 % (of 35 GHz) change in the band gap. For completeness a plot of the defect mode is included (defect a/d = 0.20).

Figure 1.2.5 shows the square of the E-field in central 7 x 7 lattice, and thus is proportional to the energy density in the mode. The defect is located in the center square. The color bar indicates the relative energy density in dB (below arbitrary level). The main features to recognize is that the mode is not isotropic in the x-y plane. It has four-fold symmetry (like the lattice) and extends preferentially in the $<10>$ and $<01>$ directions. Also note that the mode tends to concentrate in the dielectric regions, excluding itself from the holes. The holes in the sapphire are clearly seen in the 7 x 7 square lattice as relatively darker cylinders (the central lattice site is of course a defect with the smaller ID hole, a/d=0.20).
TM Mode Band Structure

\( a/d=0.45, \ \text{d}=0.213 \ \text{cm} \)

\( \text{c-axis dielectric}=11.5 \)

\[ \begin{array}{c}
\text{Frequency (GHz)} \\
\hline
0 \\
20 \\
40 \\
60 \\
80 \\
100 \\
120
\end{array} \]

\[ \begin{array}{c}
\Gamma \quad X \quad M \quad \Gamma \\
\hline
\end{array} \]

\[ k_{\parallel} \]

Figure 1.2.1
Square lattice of holes in sapphire, c-axis
d=0.084"
(Gap in % noted)

Figure 1.2.2
Square Lattice of Holes in sapphire, c-axis
d=0.084"
(Gap noted in %)

Figure 1.2.3
Square Lattice of Holes in sapphire, c-axis
a/d=0.45, d=0.084"

Figure 1.2.4
1.3 CALCULATION OF Q

In achieving a high Q, low phase noise device, we need an understanding of what fundamental factors determine the Q we expect to see. Q is defined by

\[ Q = \frac{\omega_0 U}{P} \quad (1.3.1) \]

where \( \omega_0 \) is fundamental freq. (= 35 GHz), U is energy stored, and P is energy loss rate. There are three primary loss mechanisms. They are confinement losses, wall losses, and dielectric losses. We will address each in turn.

1.3.1 CONFINEMENT LOSSES

Confinement losses refer to the losses due to the defect mode extending beyond the edges of the two dimensional dielectric lattice. The defect mode is essentially contained within an envelope that exponentially decays away from the defect site in the x-y plane. For the modes that we have been investigating the localization length is very approximately 2d (twice the lattice spacing). In other words, the field amplitudes go as

\[ E \sim E_0(x, y)e^{-r/2d} \quad (1.3.2) \]

where r is the radial distance from the defect site, and \( E_0 \) is a function dependent upon the details of the defect mode. The total energy in the fields is obtained by integrating over the (infinite) plane (introducing an error of order unity)

\[ U = \frac{1}{8\pi} \int \varepsilon E_0^2 dV \]

\[ = \varepsilon E_0^2 bd^2 \]

\[ = \frac{4}{\varepsilon} \quad (1.3.3) \]

where h is the structure thickness or plate separation.

The power lost by exiting the edge of the finite structure is found by integrating the Poynting vector around the perimeter:

\[ P = \frac{c}{4\pi} \int (E \times H) \cdot da \]

\[ = \frac{c\varepsilon E_0^2}{2} Re^{-r/4d} \quad (1.3.4) \]
where the integration is around the perimeter of the structure of radius $R$ and height $h$. For this calculation we assume a radially symmetric mode (which as we have seen in Figure 1.2.5 is not correct. Nonetheless, the true loss will be within a factor of the order of unity, and will ultimately be unimportant). Defining $n=R/d$ as the number of lattice sites from the defect site to the lattice edge, we get

$$Q \approx 0.5 e^{\frac{e^n}{n}}$$

(1.3.5)

So far as confinement losses are concerned, increasing the number of lattice sites between the defect site and the edge of the structure can quickly increase the limiting $Q$ due to confinement losses, so long as the localization length is not seriously compromised.

### 1.3.2 WALL LOSSES

The losses due to surface resistance of the plates confining the mode to two dimensions are another source of losses that, as we will see, are the most important at this time as they will probably set the ultimate $Q$ we can expect. The losses due to the surface resistance of the conducting walls is given by

$$P = \frac{1}{2} R_s \int H_T^2 dS$$

(1.3.6)

where $R_s$ is the surface resistance, $H_T$ is the tangential component of the magnetic field at the surface (recall there is no normal component in the TM mode). The total energy in the defect mode can be related to the magnetic field component by

$$U = \mu_0 \int H_T^2 dV = \mu_0 h \int H_T^2 dS$$

(1.3.7)

The $Q$ is then easily calculated as

$$Q = \frac{\omega_0 U}{P} = \frac{\omega_0 \mu_0 h}{R_s} = \frac{553 \Omega}{R_s}$$

(1.3.8)

for $f_o=35$ GHz and $h=0.080"$. 

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Recent reports of surface resistance for YBCO at 77 K indicate $R_s = 1.5 \, \text{m}\Omega$ at 35 GHz [9]. This corresponds to $125 \, \mu\Omega$ at 10 GHz where the surface resistance is usually reported. (The surface resistance goes as $\omega^2$). Using this value, we obtain an expected wall loss limited $Q$ of $3.7 \times 10^5$. As can be seen from the derivation of the wall loss $Q$, this mode can only be improved by increasing the thickness of the structure, thus increasing the volume to surface ratio, or by decreasing the surface resistance. Hybrid modes that will be discussed later may provide another way of increasing the $Q$ by allowing a greater plate separation and by promoting defect modes that do not have a strictly uniform dependence on $z$.

1.3.3 DIELECTRIC LOSSES

The $Q$ due to the intrinsic losses within the sapphire dielectric is given by

$$Q = \frac{1}{f_m \tan \delta} \quad (1.3.9)$$

where $f_m$ is the fraction of the mode energy within the dielectric (less than, but of the order unity), and $\tan \delta$ is the loss tangent of the dielectric. Sapphire has been selected in part because of its low loss tangent, $\sim 2 \times 10^{-5}$ at room temperature, $1 \times 10^{-7}$ at 77 K, and $2 \times 10^{-9}$ at 4 K. With the limitation imposed by the surface losses, we don’t anticipate the dielectric losses being of major concern.
2. HYBRID MODES

2.1 THEORETICAL DESCRIPTION OF HYBRID MODES

The lowest mode available for a two dimensional photonic band gap has electric field in the z-direction only. Close spacing of the conducting plates cuts off higher order modes which might interfere with the lowest mode. In general, these modes have x, y, and z electric field components that depend not only on the two dimensional lattice parameters, but also on the conducting plate separation, or z dimension. As part of our theoretical investigation, we looked at the higher order modes for two reasons. We need to know the maximum separation that can be tolerated before higher order modes can propagate within our projected stop band. Since we expect our Q to initially be limited by the surface resistance of the conducting surfaces, we want to maximize the volume to surface ratio by maximizing the separation. Secondly, it may be possible to find and exploit a band gap within the higher order band structure. If a configuration can be found where stop bands can be overlaid, we may be able to increase the device performance by confining a proportionally greater part of the defect mode within the dielectric material and away from wall loss mechanisms.

In the hybrid modes, we allow the fields to vary in the z-direction (perpendicular to the two-dimensional plane). We begin with Maxwell’s Equations

\[
\begin{align*}
\nabla \times H &= \frac{1}{c} \frac{\partial D}{\partial t} \\
\nabla \times E &= -\frac{1}{c} \frac{\partial H}{\partial t}
\end{align*}
\]

(2.1.1)

Consistent with our current design using sapphire as the dielectric, the dielectric constant is not isotropic, but has a uniaxial asymmetry along the c-axis. In our case the c-axis is coincident with the z-direction, so we have distinct dielectric constant along the z-axis, denoted by \( \varepsilon^z \), from the in-plane dielectric constant, denoted by \( \varepsilon^\perp \). Equation (2.1.1) can be explicitly written as
\[
\begin{align*}
\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} &= i \frac{\omega}{c} \epsilon^T(x, y)E_x \\
\frac{\partial H_y}{\partial z} - \frac{\partial H_z}{\partial x} &= i \frac{\omega}{c} \epsilon^T(x, y)E_y \\
\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial y} &= i \frac{\omega}{c} \epsilon^T(x, y)E_z \\
\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} &= -i \frac{\omega}{c} H_x \\
\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -i \frac{\omega}{c} H_y \\
\frac{\partial E_x}{\partial x} - \frac{\partial E_y}{\partial y} &= -i \frac{\omega}{c} H_z
\end{align*}
\]

(2.1.2)

The H field components can be eliminated in favor of E-field components to yield the following:

\[
\begin{align*}
-\frac{\partial^2 E_z}{\partial y^2} - \frac{\partial^2 E_y}{\partial z^2} + \frac{\partial^2 E_z}{\partial x\partial y} + \frac{\partial^2 E_z}{\partial x\partial z} &= \frac{\omega^2}{c^2} \epsilon^T(x, y)E_x \\
-\frac{\partial^2 E_z}{\partial x^2} - \frac{\partial^2 E_x}{\partial z^2} + \frac{\partial^2 E_z}{\partial x\partial y} + \frac{\partial^2 E_z}{\partial y\partial z} &= \frac{\omega^2}{c^2} \epsilon^T(x, y)E_y \\
-\frac{\partial^2 E_z}{\partial x^2} - \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_z}{\partial x\partial z} + \frac{\partial^2 E_z}{\partial y\partial z} &= \frac{\omega^2}{c^2} \epsilon^T(x, y)E_z
\end{align*}
\]

(2.1.3)

The Bloch statement for propagation in a periodic dielectric requires that the solution be periodic in the lattice:

\[
\begin{align*}
E_x(x + d, y + d, z) &= e^{ik\cdot d} e^{i\beta d} E_x(x, y, z) \\
E_y(x + d, y + d, z) &= e^{ik\cdot d} e^{i\beta d} E_y(x, y, z) \\
E_z(x + d, y + d, z) &= e^{ik\cdot d} e^{i\beta d} E_z(x, y, z)
\end{align*}
\]

(2.1.4)

where the lattice constant is d. Finally we impose the boundary condition that the tangential electric fields must be zero at the surface of the conductors:

\[
\begin{align*}
E_x(x, y, 0) &= E_x(x, y, h) = 0 \\
E_y(x, y, 0) &= E_y(x, y, h) = 0
\end{align*}
\]

(2.1.5)

where h is the plate separation. The lowest frequency solutions to Equation. (2.1.3) will have electric field components with one half cycle along the z-direction between \(z=0\) and \(z=h\). Explicitly,
Thus, as expected, we need to solve for a two-dimensional solution, and the full three dimensional solutions will be formed from the relations (2.1.6). Substituting the solutions (2.1.6) into (2.1.3) gives us the set of second order equations we need to solve.

\[
\begin{align*}
-\frac{\partial^2 \tilde{E}_x}{\partial y^2} + q^2 \tilde{E}_x + \frac{\partial^2 \tilde{E}_y}{\partial x \partial y} - q \frac{\partial \tilde{E}_z}{\partial x} & = \frac{\omega^2}{c^2} \epsilon^T(x,y) \tilde{E}_x \\
-\frac{\partial^2 \tilde{E}_y}{\partial x^2} + q^2 \tilde{E}_y + \frac{\partial^2 \tilde{E}_x}{\partial y \partial x} - q \frac{\partial \tilde{E}_z}{\partial y} & = \frac{\omega^2}{c^2} \epsilon^T(x,y) \tilde{E}_y \\
-\frac{\partial^2 \tilde{E}_z}{\partial x^2} - \frac{\partial^2 \tilde{E}_x}{\partial y^2} + q \frac{\partial \tilde{E}_y}{\partial x} + q \frac{\partial \tilde{E}_x}{\partial y} & = \frac{\omega^2}{c^2} \epsilon^T(x,y) \tilde{E}_z
\end{align*}
\]  

(2.1.7)

Note that the dielectric constants have x,y dependencies reflecting the lattice of holes within the dielectric slab. These equations are numerically solved by a finite difference method that has been developed at UC San Diego by the collaborating effort there. The essentials of the method involve making the substitution \( \tilde{E} = 1/\sqrt{\epsilon} f \), and rewriting (2.1.7) as finite difference equations. The resulting equation has the matrix form

\[
\begin{align*}
\bar{M} \bar{f} & = \omega^2 \bar{1} \bar{f} \\
\bar{M} = & \begin{pmatrix}
\frac{\omega^2}{c^2} & 0 & 0 \\
0 & \frac{\omega^2}{c^2} & 0 \\
0 & 0 & \frac{\omega^2}{c^2}
\end{pmatrix}
\end{align*}
\]  

(2.1.8)

The rank of the matrix \( \bar{M} \) is \( 3N^2 \), where \( N \) is the number of grid points in one spatial direction. In most of the following calculations, the unit cell is discretized into an 11 x 11 grid. Diagonalizing matrices such as above by conventional methods requires storage elements of order (rank)^2 and computation time increases as (rank)^3. The calculation time can quickly become very prohibitive. However, these matrices are sparse, meaning most of the elements are zero (the finite difference equations tie only nearest neighbors together, so that only elements near the diagonal are non-zero). There exist Lanczos algorithms [8] which are publicly available that are quite useful in this type of problem. The routine requires a user supplied subroutine that performs the \( \bar{M} \bar{f} \) product.

Even with the relatively quick diagonalization provided by the above routine, the band structure calculations are still laborious enough that routine exploration of parameter space is not economical. Thus, in the following calculations we concentrated mainly on our first objective, looking at bandstructures resulting from design parameters similar to those indicated by the TM calculations and
determining what maximum plate separation could be tolerated before propagating hybrid modes appear in the fundamental stop band.

2.2 CALCULATED PARAMETERS FOR HYBRID MODE BAND STRUCTURE AND DEFECT MODE

2.2.1 HYBRID MODE BAND STRUCTURE

The band structures associated with the hybrid modes are characterized by the same parameters as the TM modes with the added dependent parameter of the structure height $h$ (or plate separation). For these solutions we are considering only the lowest order modes, where the $z$-dependence has half wavelength between the plates. Of course solutions with integer number of half wavelengths exist, but these occur at higher frequencies and do not play a role.

As with the TM modes, these solutions can be scaled appropriately and used at any desired frequency or lattice spacing. Thus we obtain solutions which are functions of the hole radius to lattice spacing ratio $a/d$, and of the plate separation or structure height to lattice spacing ratio $h/d$. As we have nominally settled on a $a/d$ ratio of 0.45 for the TM mode, we used this as a starting point for the investigating the hybrid modes.

Figures 2.2.1 through 2.2.7 show the band structures obtained when the plate separation is varied from 0.5 of the lattice spacing to twice the lattice spacing. The hybrid mode frequencies increase as the plates are brought together, and the bands become flatter with smaller corresponding phase velocities. We have verified that the values agree with the analytic degenerate values obtained by Maradudin, et. al. [10], for the inverse case of dielectric rods in vacuum as the plate separation tends to zero, in particular

$$f_i = \frac{nc}{2h\sqrt{\varepsilon_i}} \quad (2.2.1)$$

with integer $n$ and the subscript $i$ referring to the dielectric of the material and vacuum.

Figure 2.2.8 shows the minima and maxima of each of the six lowest bands as a function the $h/d$ ratio, which can be thought of as the plate separation in the case of fixed $d$. For small $h/d$, the possible modes are restricted to higher frequencies, effecting a cutoff frequency. These tend towards degenerate band structures which are of little use to us. We note that the lowest band reaches our design frequency of 35 GHz at a $h/d$ ratio slightly greater than 1. Further there is little indication of any
gap opening up near the target of 35 GHz at any larger h/d. A gap is observed at nearly twice this frequency between bands 5 and 6, denoted in Figure 2.2.8 as $G_{5,6}$.

Figures 2.2.9 through 2.2.12 show the band structures that result as the h/d ratio is held at 1.50 and the a/d ratio is varied. Together with Figure 2.2.3, these span the range of $a/d=0.39$ to $a/d=0.47$. Figure 2.2.13 summarizes the results by showing the band edges of the lowest 6 bands as a function of $a/d$. The bands tend to rather uniformly increase with $a/d$. The previously observed gap $G_{5,6}$ is seen to open at the upper end of this range. For the present design with $d=0.213$ cm or 0.084”, an $a/d$ ratio of 0.47 implies a web thickness of just 0.005”. The ceramic and sapphire fabricators we have contacted have no experience producing this kind of structure and expressed hesitance to attempt such tolerance on more than on a best effort basis, and so we have opted to initially produce a structure with a higher probability of success.

There is potential to exploit this gap by designing a lattice at $2f_o$ and overlaying a TM mode gap; however, this gap is only about 3% and would probably yield too long a localization length. A better solution would probably involve looking to other lattice designs and dielectrics to optimize the location and width of stop bands (this particular simulation assumed the anisotropic dielectric constant with the c-axis in the z-direction). The extensive CPU time required to generate each of these simulations prohibited a more thorough investigation of all the possibilities. Additionally, the software that generates these solutions does not systematically converge. A number of problems can occur which will yield either no solution or worse, a false solution. An understanding of the particular characteristics of a problem is required to properly tune the software.

2.2.2 HYBRID DEFECT MODE

Although we don’t anticipate using the hybrid mode band structure or a hybrid defect mode, we did nonetheless establish the existence of these defect modes. We include an example of a defect mode in the central 3 x 3 lattice in Figure 2.2.14. This mode is for the inverse case of cylindrical dielectric rods in a square lattice, where there exists a larger gap. Shown are a sequence of plots, time slices 45 degrees apart ($\Theta=\omega t+\delta$), depicting the E-field at either conducting surface. The symmetry of the mode indicates this mode is doubly degenerate. We would not use such a mode, and instead would look to split the degeneracy by introducing an off-axis asymmetry in either the underlying lattice or the defect itself.
Hybrid Mode Band Structure
a/d=0.45, h/d=0.50, d=0.213 cm

Figure 2.2.1
Hybrid Mode Band Structure
a/d=0.45, h/d=0.70, d=0.213 cm

Figure 2.2.2
Hybrid Mode Band Structure
\(a/d=0.45, h/d=1.00, d=0.213 \text{ cm}\)

Figure 2.2.3
Hybrid Mode Band Structure
a/d=0.45, h/d=1.10, d=0.213 cm

Figure 2.2.4
Hybrid Mode Band Structure
\(a/d=0.45, \ h/d=1.25, \ d=0.213\ \text{cm}\)

Figure 2.2.5
Hybrid Mode Band Structure
a/d=0.45, h/d=1.50, d=0.213 cm

Figure 2.2.6
Hybrid Mode Band Structure
a/d=0.45, h/d=2.00, d=0.213 cm

Figure 2.2.7
Hybrid Mode Band Minima and Maxima (n=1,2,3,4,5,6)
Square Lattice of a/d=0.45 holes in Dielectric

Figure 2.2.8
Hybrid Mode Band Structure

\( a/d = 0.47, h/d = 1.50, d = 0.213 \text{ cm} \)

**Figure 2.2.9**
Hybrid Mode Band Structure
a/d=0.43, h/d=150, d=0.213 cm

Figure 2.2.10
Hybrid Mode Band Structure
\( a/d = 0.41, \ h/d = 1.50, \ d = 0.213 \text{ cm} \)

Figure 2.2.11
Hybrid Mode Band Structure
\(a/d=0.39, h/d=150, d=0.213\ cm\)

Figure 2.2.12
Hybrid Mode Band Minima and Maxima (n=1,2,3,4,5,6)
Square Lattice of varying a/d ratio
h/d=1.50

Figure 2.2.13
Figure 2.2.14
3. FABRICATING THE PBG STRUCTURE AND TEST FACILITY

3.1 SAPPHIRE WAFER AND DEFECT MANUFACTURING

As a result of discussions with a number of potential fabricators of the PBG structures, several important factors emerged which suggested an initial test structure of 15 x 15 lattice size. The vendors with whom we spoke encompassed several fabrication techniques including laser drilling, direct growth of the lattice, stationary and rotary ultrasonic drilling. Common among all the companies was the fact that none had experience producing structures similar to what we ultimately wanted. We will briefly mention each technique.

Saphikon (NH) can directly grow single crystal sapphire using a technique known as Edge-defined Film Growth (EFG). In this technique, molten sapphire is flowed upward through a capillary onto the central portion of a Mo plate. It then flows along the (heated) plate, growing upward. Areas on this plate which have been machined away then define edges, and the molten stock will not flow across these edges into the recession. Thus a long single crystal may be grown with a cross-section defined by the Mo plate may be grown. Our plan involved growing a boule of crystal with the PBG cross-section, then slicing to obtain the desired thickness. The advantage to us would be that with a single growth we could obtain many pieces. Unfortunately, they have not as yet grown any crystal with a 4” diameter, and have no experience producing a complicated structure such as ours. Also, the sapphire grown in this manner could not approach the purity that can be achieved through zone refinement growth such as is available through Crystal Systems (MA).

The laser drilling option would require drilling through thinner sapphire wafer, of perhaps 0.025”, and stacking several pieces to achieve the desired thickness. Laser drilling requires small aspect ratios, whereas we are targeting for an aspect ratio of near unity (diameter:thickness). The lasing action generates heat that would affect the thin webs and it might be expected that the walls in these areas would deflect significantly. For this type of drilling, it became apparent that an Eximer laser would be necessary. Resonetics (NH) seemed the most promising among the vendors we spoke with. Cost would be high, and the prospect of stacking wafers, while with some advantages, is undesirable.

We ultimately chose ultrasonic drilling. There are two ways of drilling ultrasonically, rotary and stationary. In rotary drilling, the bit is rotated at high speed (~8 kHz) in addition to ultrasonic action. This type of drilling can produce the high quality holes with good precision. The cost is high as each hole is individually drilled, and for the full-size structure there are around 1500 holes per wafer. A typical price is $4 - $7 per hole ($0.75/min. drilling costs, with est. 5-10 min. per hole), thus each full size PBG structure can be expected to be very expensive even with a volume discount.
The second type of ultrasonic drilling is stationary. The advantage of this method that it can use a fabricated (usually Tungsten) bit with multiple perforators, thereby it can perform drilling of multiple holes at a time. It is conceivable to drill all the holes in a single pass. The drilling grit contained in a slurry must be kept flowing adequately through all the hole sites. We discussed fabrication with Bullen Ultrasonics (OH), and it was decided to produce initially a 15 x 15 test piece. There are a number of reasons why we chose to produce a smaller test piece initially rather than opt for a full size piece.

There is first of all the question of how adequate any machining process would be. With a smaller less expensive test structure we can answer some of the questions without making a heavy financial commitment to an unknown process. Adjustments if necessary can be made to the final specifications. Also, Bullen charges a one time tooling charge for fabrication of the drilling bit. Additional pieces can be drilled without incurring this tooling charge. We chose 15 x 15 because it is possible to replicate this size lattice 3 times side by side and cover the width of our 4” diameter full size wafer, or completely fill the wafer with holes with 9 drilling actions. A single 15 x 15 size was projected to still give a respectable Q of the order of 1000, sufficient to answer many questions.

As it turned out, Bullen actually accomplished the 15 x 15 lattice with two separate drillings. They manufactured a bit consisting of every other row of holes to allow adequate flow around each hole site, and then followed up by drilling in a second pass the intervening rows of holes. For the test structure, the cost was $1100, including a little over $500 for a one time tooling charge. The full size lattices were fabricated at a cost of $1600 each.

The specifications for the 15 x 15 lattice are shown in Figure 3.1.1. They called for holes of 0.076” diameter, spaced by 0.084” over a lattice size of 15 x 15. The sapphire was obtained internally at no cost, and had a diameter of 3” and a thickness of 0.062”, close enough to the design thickness of 0.080” that we felt it unnecessary to purchase a separate custom sapphire piece for the purpose. Shown in Figure 3.1.2 is a photograph of the sapphire PBG dielectric as returned from Bullen. We discovered that the piece is still quite rugged, and after some handling are quite confident that ultimately any structure with similar dimensions will not suffer from any special mechanical fragility. It is easily handled by hand, using normal precautions, with no consequence. Observations under the microscope showed that the holes had small exit chips of several mils which we expected would have only minor impact. The holes had diameters of 0.0745” (+/- 0.0005”), with a definite taper of up to 0.001”. The spacing seems to be very close to the 0.084” specification.

Bullen indicated two strikes were necessary to achieve this piece. Of the remaining wafer(s), we sent a larger piece to Advanced Tool Concepts (CA), from which they
machined a number of small cylinders which fit snugly inside the lattice holes. Figure 3.1.3 shows the specifications for these defects. ATC machined these using a three step process. Using the remainder of the sapphire wafer insured the defect thickness would be correct. First they core drilled to oversized (+0.010") disks. The inside diameter was then core drilled to the required dimension, and finally the outside diameter was taken down to specification by grinding on a precision lathe. On the later stage of the project defects of 0.046", 0.051", 0.055" and 0.060" ID were manufactured.

Shown in Figure 3.1.4 are the specifications for a full size lattice in a 4” wafer. These sapphire wafers were obtained from Crystal Systems. They are Hemlite White quality (obtained from 99.996% pure stock using the Heat Exchanger Method, which further enhances the purity through zone refinement). They are 4” in diameter, 0.080” thick with 80-50 polished faces, obtained at a cost of $678 each.

One of the PBG structures is shown in the photograph in Figure 3.1.5. One defect is readily apparent in the photograph about 1/3 of the way from the right edge just below the centerline. This defect appears to be on the exit of a hole where a clean exit did not occur over about 1/3 of the full circumference. We do not anticipate this will be of significant consequence, as it is 11 lattices to the left and 3 lattice sites below the center. The other structure appears to have fewer and smaller abnormalities.

Figures 3.1.6 and 3.1.7 show sapphire PBG structure fragments and defects. The photographs have been taken under the microscope with amplification of 50.
Scale 4:1
Holes in a 0.060" Sapphire piece
on a 15 x 15 lattice
Lattice cut out no more than 0.030" beyond outside set of holes

Figure 3.1.1
Figure 3.1.3

Series of ID's:

0.048"
0.044"
0.040"
0.036"
0.032"
0.028"
0.024"
0.020"
1. Hole size = 0.076" (+/- 0.002")
2. Hole to hole distance = 0.084" (+/- 0.002") on centers
3. Supplied wafer size = 4" (+/- 0.010"
4. Sapphire disk thickness=0.080"

Additional:
1. Assuming the holes put in using the 15 x 15 pattern from the previous piece, and this 15 x 15 array is replicated over the whole disk, the central hole in the disk should also be the central hole of the 15 x 15 array. then there would need to be eight more such arrays to complete the disk (total of 45 x 45, which will comprise a square covering 4" disk).
2. Each 15 x 15 array would need to be in registration with j neighboring arrays within 0.002".
Sapphire PBG Structure Fragments

Figure 3.1.6
PBG Structure Defect

Figure 3.1.7
3.2 PHOTONIC BAND GAP STRUCTURE

3.2.1 COUPLING PORTS

Several ways of coupling microwaves into a band gap structure have been attempted. One technique is shown in Figure 3.2.1. The microwave power passes above the PBG structure within waveguide. Downstream of the structure is a movable or sliding short which provides reflection of the incident power. This sets up a vertical standing wave in the waveguide above the lattice. A small hole in the waveguide provides a coupling mechanism into the lattice. The waveguide mode is such that the E-field is perpendicular to this side, and thus is parallel to the E-field in the TM mode within the PBG structure. By sliding the position of the short, the standing wave nodes within the waveguide can be positioned with respect to the coupling hole, and provide a means of dynamically varying the coupling strength.

Another way of coupling microwave energy into the PBG from the waveguide has been used (see Figure 3.2.2). A waveguide in this case is directly coupled into the PBG supporting plate separation. The E-field in the waveguide is vertical, coinciding with the E-field in the PBG. This method of coupling has been successfully used for observing direct in plane transmission spectra. This requires a ramp to transition from the waveguide height to the plate separation. Also, traveling modes around the perimeter can exist and must be attenuated using microwave absorber. Ultimately, this method has significant VSWR and does not allow variable coupling.

Most of the transmission and reflection experiments with PBG and defect mode have been implemented using an antenna type coupling port (see Figure 3.2.3). The microwave energy comes from the semi rigid coaxial cable where the outer conductor is connected to the supporting plates and the inner conductor protrudes into the dielectric volume.

3.2.2 NIOBIUM SUPPORTING PLATES

The niobium supporting plate design was largely concerned with the positioning of the coupling ports. The goal was to avoid strong perturbation from the coupling while maintaining total insertion loss of the structure to less than about 10 dB. Based on a series of transmission and reflection experiments, the following design (see Figure 3.2.4) has been implemented. One coupling port is placed in the top plate and one in the bottom, each of them located 5 lattice spaces from the center in <01> direction of the lattice. The threaded holes for holding the PBG structure together has been arranged so that there are options available for 10, 8 and 6 lattice spaces (<01> direction for sapphire lattice) separation between coupling ports. This is accomplished by rotating the plates with respect to each other.
3.2.3 HTS COMPOSED SUPPORTING PLATES

The layout for composed HTS supporting plates for the PBG structure is presented in Figure 3.2.5. The design of coupling ports is similar to that for the niobium supporting plates. The HTS YBCO films are deposited on sapphire substrates of 2.000” diameter and 0.020” thickness (see Figure 3.2.6) and inset into copper plates. It has been concluded from a number of measurements and theoretical calculations that more than 90% of the defect mode energy is concentrated within the central 15 lattice spaces around a defect. Thus, a 2” diameter HTS film is large enough to cover most of the distributed field of the defect mode.

The advantages of this structure are the following:

It is easier and less expensive to deposit a high quality 2” diameter HTS film than a 4” diameter film.

The coupling ports enter through the copper plates, not through HTS films on sapphire substrates. In this way we minimize leakage of microwaves from coupling ports into the sapphire substrates, (or LaAlO$_3$ if this is used, as LaAlO$_3$ also has a high dielectric constant). The high dielectric value of the substrates are of particular annoyance from the point of view of microwave leaks and possible additional spurious resonances.
Coupling the Microwaves through the Hole in the Waveguide
Figure 3.2.1
Direct Coupling the Microwaves from the Waveguide into the Supporting Plate Separation

Figure 3.2.2
Antenna Type Coupling Port

Inside Conductor

Dielectric

Outside Conductor

PBG Supporting Plate

Figure 3.2.3
Niobium Supporting Plate Design
Figure 3.2.4

Nb Bottom Plate of PBG Structure

4-40 tapped through
Figure 3.2.5

HTS Supporting Plate Design

Figure 3.2.5
Substrate for HTS Film

Figure 3.2.6
3.3 CRYOGENIC SYSTEM FOR OPERATING AT LIQUID HELIUM TEMPERATURES

The cryogenic system for operating at liquid helium temperatures has been designed to support two PBG structures. The system layout is presented in the Figure 3.3.1. To provide low thermal conductivity and equal thermal contraction of all parts the system has been manufactured from stainless steel.

The PBG structure is mounted on the brackets, with the input and output coaxial cables attached to the coupling ports. The coaxial cable exhibits temperature instability characteristics due to the differential thermal contraction of the Teflon dielectric with respect to the metal conductors. This can result in movement of the center conductor affecting the transmission qualities and possibly the coupling strength of the defect mode. To minimize this we use a short 6” coax section to connect the supporting plates. The PBG structure and the coax are placed inside of the vacuum can and kept at the stable temperature. Waveguides are used from the top of the vacuum can at 4.2 K to the top of the dewar at room temperature and kept under the vacuum. Air is evacuated through the vacuum pump valve from the central tube, vacuum can and the waveguides. The central tube and the waveguides has been welded inside the top plate of the vacuum can. An indium wire seal is used between the vacuum can and its top plate (where the PBG mounts) to provide vacuum seal. The waveguides at the top of the dewar are sealed using the pressure windows (O-ring and a piece of mylar sheet pressed between flanges. It was observed at room temperature that defect mode transmission and reflection spectra do not change significantly when a piece of mylar is placed in one of the cross sections of the waveguide).

The estimated attenuation for two sections of 3 foot stainless steel waveguide (input and output for one PBG structure) is on the order of 20 dB. To reduce the system attenuation, the inside surfaces of the waveguides have been silverplated. A search revealed that silverplating inside a long narrow rectangular tube (.28 x .14 inch waveguide inner dimension) is not a trivial task for most silverplating companies. They do not fit to standard equipment and procedures, and required the manufacturing of special facilities. A company named BrushTek has completed our task at the lowest price. Prior to silverplating, the waveguides were welded into plates as is shown in Figure 3.3.2. Subsequently, the silverplating of waveguide’s inside surfaces was done.

The helium boil-off for the cold dewar with the system in steady state is about 5 liters per day. When the system is precooled to 77 K using liquid nitrogen, it requires approximately 16 liters of liquid helium to lower the temperature down to 4.2 K. In contrast, it takes approximately 30 liters of liquid helium to cool the system from the room temperature down to 4.2 K directly.
Cryogenic System Layout for the PBG Resonator Operating at 4.2 K.

Figure 3.3.1
Figure 3.3.2
3.4 EXPERIMENTAL SETUP

3.4.1 EXPERIMENTAL SETUP FOR TRANSMISSION AND REFLECTION MEASUREMENTS

Four experimental setups are depicted in Figure 3.4.1. A HP 8690B Sweep Oscillator with a 8697A 26.5-40 GHz plug-in module generates the microwave sweep. An isolator is placed immediately on the plug-in output to eliminate reflections. A 10 dB directional coupler extracts power to a R422A diode detector which is used in feedback to provide automatic leveling of the sweeper output power. A frequency meter is used to establish frequency ranges and a phase shifter to provide the smallest VSWR in the system. A variable attenuator provides an attenuation pad, and the incident power is measured via an additional 10 dB port to a thermistor type power sensor.

In one type of experimental arrangement, this power is then incident upon the lattice holder, and is coupled directly into the space between the plates and is thereby incident upon the edge of the sapphire. The power transmitted through the lattice then enters the waveguide coupled into the plate separation on the opposite side of the structure, and the transmitted power is measured by a power sensor. In more recent data, this sensor has been the HP R8486A connected to an HP 436A power meter. In this arrangement, the lattice can be oriented so that the primary transmission is in the <10> direction (along an x- or y-axis), or it can be rotated 45 degrees to look at a simulated <11> transmission spectra. In addition, these can be taken with or without various defects in the lattice.

In second and third types of experimental arrangement, microwave power is delivered to the PBG from a waveguide through a waveguide-to-coax adapter and coaxial cable. It couples through an antenna type coupling port. The cryogenic system described in the previous chapter is set up for this type of measurement. Power transmitted through the PBG structure couples another antenna-type port through a coax-to-waveguide adapter and is measured by the HP R8486A power sensor. Reflection measurements, as depicted in the third experimental arrangement, are measured by HP R8486A sensor from the 10 dB directional coupler output.

The final experimental arrangement in Figure 3.4.1 is for transmission and reflection measurements with the waveguide coupling port. The basic components in this circuit are analogous to those described above.
3.4.2 EXPERIMENTAL SETUP FOR CLOSED-CIRCUIT OSCILLATOR

The block-diagram for a closed circuit oscillator based on a PBG resonator is shown in Figure 3.4.2. The signal from the PBG resonator is amplified with a low phase noise amplifier and fed back to a resonator. An isolator and attenuator are used to reduce reflections and control the power in the circuit. By adjusting the phase shifter, maximal energy for a defect mode can be established in the oscillator circuit. The phase shifter is used to set the total phase shift of circuit to an integral number of cycles. The steady state power level is achieved when the amplifier gain is equal to the total losses of the circuit. 10 dB directional coupler is used to provide an oscillator output for defect mode frequency and quality factor analysis.
Experimental Setup for Transmission and Reflection Measurements

a - Experimental setup for direct in plane transmission

b - Experimental setup for transmission measurements where the energy is coupled through an antenna type coupling port
c - Experimental setup for reflection measurements where the energy is coupled through an antenna type coupling port

d - Experimental setup for transmission and reflection measurements where the energy is coupled through the waveguide
Experimental Setup for Closed Circuit Oscillator on the Base of PBG Resonator

Figure 3.4.2
4. EXPERIMENTAL DATA AND DISCUSSION

4.1 PRELIMINARY TEST WITH 15X15 SAPPHIRE LATTICE

The initial tests done with the 15x15 lattice test structure involved verifying the nominal stop band behavior expected of the lattice without a defect present. Direct transmission through the sapphire is used. Because of mismatch at the entry and exit to the lattice holder, we encountered problems properly calibrating the transmitted energy to the incident. The reflected spectra typically shows numerous (low Q) resonances. Inherent in making measurements at mm-wavelengths are problems with strong in-line reflections. It is typically difficult to eliminate them, making frequency sweep-type measurements troublesome. We will see data indicating this shortly.

Shown in figure 4.1.1 is the transmission spectrum in the <10> direction. The power is the directly measured power, and is not scaled to the incident power. This figure shows a broad stop band extending well beyond the expected stop bandwidth of 4 GHz. From the band structures we note that in certain directions the band can be considerably broader, and in fact, in any one single direction, propagating modes can be excluded from a larger portion of the frequency spectrum.

Our microwave sweeper extends up to 39.5 GHz, and in the <10> direction we don't see transmission at any of the higher frequencies up to this limit. Calculations also show that the expected transmission through a lattice of this size will be attenuated by about 60 dB within the stop band. Given the available power (typ. 2 mW with ALC), we don’t have the dynamic range to be sensitive to this even if the power were efficiently coupled into the PBG structure. Thus the data represents the limits of the detectable power as well as the presence of the stop band.

By rotating the lattice 45 degrees, we can look in the <11> direction. Because of the shape of the PBG structure, we need to be careful to place absorber around the lattice in such a way as to limit leakage. Figure 4.1.2 shows the directly measured transmitted power. The stop band appears narrower, and roughly centered at 35 GHz. The various low level transmissions seen in the range of 33-37 GHz are probably due to modes propagating near the edge of the lattice where band structure calculations do not apply. It was noticed that small movements of the surrounding absorber caused sharp changes in the transmitted power, indicating some proximity effect.

Figure 4.1.3 shows the effect of inserting a defect cylinder into the center hole of the 15 x 15 lattice. In this figure the transmission in the <10> direction is again displayed, and the defect mode near 37.2 GHz is seen. Changes in the background at lower frequencies are noted. These type of changes are common when the lattice holder is disassembled and reassembled.
The position of the defect modes are very sensitive to the assembly of the lattice holder, and how the plates are pressured against the sapphire. Increasing or decreasing the pressure against the PBG lattice can change the position of the defect mode by several hundred MHz. It is believed that the pressure is altering the close gap between the sapphire and the dielectric. Screws located outside the lattice areas effect a small amount of bowing near the center of the lattice, increasing the plate separation there. This effectively reduces the average dielectric constant, moving the defect mode towards higher frequencies. As a rough guide, a 0.001” separation represents a nearly 2% decrease in the average dielectric constant, and according to figure 1.2.4 we would expect an increase of roughly 400 MHz in the center frequency. We do note that defect mode frequency does not necessarily follow this trend, but would require separate simulation.

Coupling through the waveguide port results in generally cleaner defect modes, as extraneous transmissions are not seen. It was found necessary to reduce the waveguide wall thickness to around 0.010”, so that the aperture thickness to diameter ratio was small and promoted penetration of the waveguide modes into the defect mode within the lattice. To do this, one side of the waveguide was removed and replaced with a thin Cu sheet with an aperture appropriately located. The required minimum aperture diameter to see a mode is approximately 0.063”, and generally we worked with a diameter of 0.073”. Because of the break in the waveguide integrity, we also improved transmission through this region of the waveguide by pressure sealing the break with Indium to give a better path for the induced waveguide currents.

In this mode it is much easier to look at transmitted power exiting the side of the structure. Shown in figure 4.1.4 is an example of such a defect mode. This mode has a Q of about 900, of the magnitude we expect to see for this lattice. Briefly we indicate the resonant line shape as a function of the Q and the center frequency, i.e.,

\[
P(\omega) \propto \frac{1}{(\omega - \omega_0 - \Delta\omega)^2 + (\frac{\omega_0}{2Q})^2} = \frac{1}{(\omega - \omega_0)^2 + (\frac{\omega_0}{2Q})^2}
\]

(4-1)

where the loaded frequency shift \(\Delta\omega\) is ignored when fitting to obtain Q. For the various modes we have looked at we obtain Q’s of between 800 and 1400 in most cases.

In figure 4.1.5 is shown the power reflected from the coupling port region of the PBG structure, that is, the power reflected from the tunable short and from the PBG port. The oscillations in the return power are typical for this setup. Without the Indium seal
along the waveguide break, these oscillations can be much larger, with minima down more than 10dB. In this situation it is difficult to locate the defect mode. One observes a sharp dip just below 36 GHz in the spectrum shown in the figure. This is the defect mode absorption.
<10> (ΓX) Transmission Spectrum
15 x 15 PBG Lattice

Figure 4.1.1
Figure 4.1.2
Figure 4.1.3
Transmission Spectra
0.036” ID Defect
Domed coupling port inside PBG Struct.

Figure 4.1.4
Power Measured following PBG coupling port with waveguide Indium seal

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>0.1</td>
</tr>
<tr>
<td>32</td>
<td>0.2</td>
</tr>
<tr>
<td>34</td>
<td>0.3</td>
</tr>
<tr>
<td>36</td>
<td>0.4</td>
</tr>
<tr>
<td>38</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 4.1.5
4.2 PHOTONIC BAND GAP STRUCTURE WITH COPPER SUPPORTING PLATES

4.2.1 PROOF OF BAND GAP EXISTENCE

To confirm band gap existence for theoretically calculated dielectric structure direct in plane transmission has been observed for two 4” diameter sapphire structures sandwiched between copper plates. Two sapphire structures have been manufactured to be identical, however, small mismatches inevitably exist. We will distinguish these structures further as N1 and N2.

Waveguide coupled into the plate separation as shown in Figure 3.2.2 and experimental setup as in Figure 3.4.1(a) have been used to conduct the experiment. Figures 4.2.1 and 4.2.2 show the transmission spectra in <01> and <11> directions for the sapphire structure N1. The band gap begins near 31 GHz for transmission in the <01> direction and near 35 GHz for <11> direction. We are not able to see transmission resuming at any frequency up to our maximum frequency of 39.5 ~ 40 GHz. The direction of transmission was varied by rotating the sapphire structure with respect to the input/output ports. Shown in the Figure 4.2.3 is the lower band edge as a function of propagation direction. As can be seen, the lower band edge, and presumably the band gap, seems to be 1.5 GHz, or more, higher than calculated.

Figures 4.2.4 and 4.2.5 show the transmission spectra in the <01> and <11> directions for the sapphire structure N2. Analogously to the structure N1, the band gap is shifted to the higher frequencies. It starts at near 35 GHz for <01> direction and at 36 GHz for <11> direction. The higher frequency band edge can be seen for structure N2 in the <11> direction. Microwave power is transmitted at near 39.5 ~ 40 GHz frequencies.

We believe that the band gap shift to the higher frequency range in comparison to the theoretical calculation can be due to the number of oversized holes in PBG structures and corresponding decrease in average dielectric constant. Figure 3.1.6 demonstrates the example of thinner than nominal size web.
Figure 4.2.1

Transmission Spectrum
PBG Sapphire Structure N1

Power (mW)

Freq. (GHz)
Figure 4.2.2
Figure 4.2.3
Figure 4.2.4
<11> Transmission Spectrum
PBG Sapphire Structure N2

Figure 4.2.5
4.2.2 EVALUATION AND OPTIMIZATION OF DEFECT MODE AT ROOM TEMPERATURE

To create a localized mode within the band gap, we introduce a defect into the lattice by filling in one of the holes with a cylinder of sapphire (see Figures 3.1.3 and 3.1.7). Cylinders with varying inside diameters, from 0.024" to 0.060" have been available for testing. We refer to the defect by its inside diameter. The sapphire structure N1 has been used in following tests.

Two antenna-type coupling ports separated by 6 lattice spaces (in <01> direction) have been constructed in copper supporting plates. By placing the defects in a lattice site near the ports, microwave energy can be coupled into the defect through one port and detected after exiting through the other port. The reflected power from the PBG structure can be also observed. The position of the defect site can be varied in order to change the relative positions of the defect and coupling port.

Reflected power spectra from PBG structure with introduced defects have been analyzed for all defect sizes and different defect sites. Two sharp absorptions corresponding to the defect modes are seen near 35 GHz and 38 Ghz, and are usually observed for every defect size. Figure 4.2.6 shows a typical reflected power spectrum for PBG with 0.024" defect, 1 lattice from coupling port in <01> direction. Both defect modes are presented in the Figure 4.2.7 vs. defect size. As theory predicts, the resonance frequency increases with the defect size (inside diameter) for both low (at 35 GHz) and high (at 38 GHz) frequency defect modes. The example of transmission spectrum for 0.032" defect is presented in Figure 4.2.8. The resonance mode for PBG with copper supporting plates at the room temperature had Q of 900 ~ 2000 magnitude.

The low frequency mode could not be excited for defects positioned more than 1 lattice space from the coupling port in the <01> or <11> directions. The higher frequency mode also could not be seen for defects positioned farther than 1 lattice space from coupling port in <11> direction, however, it could be seen for defects positioned up to 4 lattice spaces from coupling port in <01> direction. Figure 4.2.9 shows coupling strength (the ratio of average reflected from PBG power to the power at the resonance absorption) for 0.032" defect vs. number of lattice spaces in <01> direction. The results obtained for the high frequency defect mode are in the good agreement with the calculated energy density distribution from a defect mode presented in Figure 1.2.5.

Theoretically, there should be a mode for each band in the band structure, thus it is expected that there are multiple modes for a single defect. However, only one mode should be centered in the band gap and thus giving one localized, high Q mode. To distinguish between two sets of modes the following experiment was conducted. A defect was placed at 1 lattice space in <11> direction from coupling
port at the center. There is a transmission output port on the edge of sapphire (a waveguide coupled into the supporting plate separation) in the same direction from input coupling port as a defect. Figure 4.2.10 presents a transmission spectrum for described configuration with 0.032” defect. The low frequency mode being close to the frequency of a photonic band gap edge propagates all the way through the sapphire structure.

These results indicate that the higher frequency modes are nonetheless the PBG modes. We believe that the discrepancy between theoretically calculated resonance frequency and observed one is due to the oversized holes in the sapphire PBG structure.
Reflected Power from 0.024” Defect, 1 lattice in <01> Direction from Coupling Port

Figure 4.2.6
Defect Mode vs Defect Size for 1 Lattice Space in <01> and <11> Directions

Figure 4.2.7
Transmission Spectra for 0.032" Defect, 1 Lattice Space in <01> Direction

Figure 4.2.8
Figure 4.2.9
Trans. Spec. for 0.032" Defect,  
1 Lattice Space in <11> Direction  
from Input Coupling Port at the Center  
to Output at the Edge of Sapphire

Figure 4.2.10
4.2.3 EVALUATION OF DEFECT MODE AT LIQUID NITROGEN TEMPERATURES

The Q of defect modes for the PBG structure with copper plates have been evaluated at liquid nitrogen temperatures. To conduct the experiment, the PBG structure was simply submerged in liquid nitrogen. As a result of filling holes in the PBG structure with nitrogen and increasing the average dielectric constant of the structure, the resonance shifted to lower frequencies.

The coaxial cable, coupling the microwaves into the PBG structure, was partially submerged in liquid nitrogen. Thus the temperature across the coax length changed over time. We believe that differences in thermal contraction (between the coax dielectric and the metal conductor) caused changes in the coupling strength, and as a result, a strong dependence of resonance frequency upon the temperature state of the coax. Figure 4.2.11 shows the defect mode, changing with time for the PBG structure submerged in liquid nitrogen. It is concluded that the temperature of coax has to be controlled and stabilized when the PBG is used as an oscillator.

Due to lower resistive losses in copper at 77K, the Q of the defect mode improves relative to room temperature. For different defect sizes and defect sites the observed Q was in the range of 4000 ~ 12000 (see Figure 4.2.12).
<01> Transmission Spectra
032 Defect, 6 lattice between coupling ports
1-T=293K and 2-10min, 3-20min, 4-30min, 5-60min,
6-90min, 7-120min, 8-150min, 9-230min at T=77K

![Transmission Spectra Graph](image)

Figure 4.2.11
<01> Transmission Spectrum
0.032" Defect, T=77 K, Q=6650

Figure 4.2.12
4.2.4 COUPLING PORT OPTIMIZATION

Antenna-type coupling ports mostly have been used to couple microwave energy into the PBG defect. To optimize the coupling port design a series of reflection experiments for varying coupling conductor protruding length and defect position as well as transmission for varying distance between coupling ports were carried out. We observed a stronger dependence of the coupling strength upon relative positions of the defect and the conductor to the nodes of a defect mode rather than upon the conductor length. Thus the coupling strength for a defect at 1 lattice in \textit{<01>} goes through a maximum with the conductor protruding length (see Figure 4.2.13), but remains smaller than the coupling strength for a defect at 2 lattice spaces in the \textit{<01>} direction (see Figure 4.2.14 and 4.2.9). The best coupling (~7.5–9 dB at 77 K) was observed for 2 lattice space separation between a coupling port and defect (\textit{<01>} direction in sapphire structure) (see Figure 4.2.15).

The total attenuation, or insertion loss of the system with 4 lattice space separation between coupling ports on transmission is less then 10 dB. We have received total insertion losses of the system in the range of 15-20 dB at 77 K when coupling ports have been 6 lattice spaces apart and defect has been at 3 lattice spaces from coupling ports. The loss of the system has been improved by 6-10 dB at 77 K compared with the room temperature for various defects and port separations. We have not observed a signal in transmission for a 10 lattice space separation between coupling ports.

As we intended to maintain the insertion losses of the structure at about 10 dB, the appropriate coupling port separation would be 4 lattice spaces. However, it is expected to obtain lower insertion losses going from copper supporting plates at 77 K to superconducting plates. In this case a defect mode with 4 lattice space separation between coupling ports can be overcoupled and the Q of the defect mode would be lowered. Taking into consideration that we are trying to avoid strong perturbation due to the coupling, we decided to target a slightly undercoupled defect mode. To achieve this, we decided to use 6 lattice space separation between the coupling ports. The PBG structure with superconducting plates has been designed where 6, 8 and 10 lattice space separations between coupling ports are available. Coupling conductor protruding length will be the same as for antenna-type coupling ports (glass beads manufactured by Wiltron) working in the 26-40 GHz frequency range.
Coupling Strength vs Coupling Conductor Protruding Length for 0.032" Defect, 1 Lattice in <01> Direction from the Coupling Port.

Open Symbols= Room Temperature
Solid Symbols= 77 K

Figure 4.2.13
Coupling Strength vs Distance between Defect and Coupling Port for 0.032" Defect at 1 - 293 K and 2 - 77 K. Coupling Conductor Protruding Length Decreased to 80% from the Standard Length.

Figure 4.2.14
0.036" Defect Transmission Spectrum
4 Lattice Space Separation between Coupling Ports, T = 77 K

Figure 4.2.15
4.3 PHOTONIC BAND GAP STRUCTURE WITH SUPERCONDUCTING NIOBIUM SUPPORTING PLATES

4.3.1 PRELIMINARY Q EVALUATION AT LIQUID HELIUM TEMPERATURES USING PIN DIODE FOR HIGH Q MEASUREMENTS.

A photonic band gap resonator with superconducting niobium supporting plates operating at liquid helium temperatures was built. The band gap and defect mode has been investigated at 4.2 K by sweeping the frequency across the defect mode using sweep oscillator and looking in both transmission and reflection (see experimental setups in Figure 3.4.1 b, c).

Both PBG sapphire structures have been tested. Typical transmission spectra for the structures N1 and N2 with niobium supporting plates at 4.2 K are shown in Figure 4.3.1 and Figure 4.3.2, respectively. The PBG resonator with dielectric structure N1 demonstrated single defect mode with Q of 100000 ~ 150000. The PBG resonator with dielectric structure N2 had one similar to the structure N1 defect mode and several low Q resonances around 39 ~ 40 GHz. The transmission spectrum for PBG structure N2 in <01> direction between coupling ports separated by 6 lattice spaces with no defect is presented in Figure 4.3.3. It shows that the low Q resonances are unrelated to the defect. The observed defect modes for structures N1 and N2 are presented in Figure 4.3.4 vs. defect size.

The defect mode frequency increases from approximately 36 GHz to 38 GHz as the defect size increases from 0.024” to 0.044”. Thus, the resonance frequencies for the PBG with niobium supporting plates at 4.2 K are 1.5 - 2 GHz higher than the lower defect modes for PBG with copper plates at 293 K (see Figure 4.2.7). We believe that due to the sapphire dielectric constant decrease with temperature, the defect mode has shifted to higher frequency. As a result, higher defect modes (those previously seen near 38 GHz) shifted to frequencies higher than 40 GHz, and can not be detected with our equipment. The observed resonance is the lower defect mode.

Initially, the observed Q was an order of magnitude smaller than theoretically calculated. The capability of present measuring technique was questioned. Sweeping the frequency across the defect mode using a sweep oscillator and looking for transmitted power does not allow measurement of Q corresponding to half width less than the resolution of the microwave sweep oscillator. One technique for evaluating the Q is to measure the time constant of stored energy decay in the resonator. It follows from the definition Q that the energy dissipation with time in a cavity depends upon the Q as given by:

\[ U(t) = U_0 e^{-\omega t/Q} \]  

(4.3.1)
where $U_0$ is initial amount of energy stored in the cavity, $U(t)$ is energy in the cavity at the time $t$, and $\omega$ is the resonance frequency. The incoming power to the resonator was switched off using a PIN diode, and the energy decay as sensed by microwave crystal detector is recorded on an oscilloscope screen. The PIN diode provides a switching time less than 20 ns (see Figure 4.3.5) and isolation of 30 dB. A typical energy decay measured during initial test is presented for 0.040" defect in the Figure 4.3.5. It corresponds to a Q of 125000.

A closed circuit oscillator has been built based on this PBG resonator. The block-diagram of the oscillator with 10 dB directional coupler output for measuring power and frequency is presented in Figure 3.4.2. After adjusting the phase shifter and attenuator, a very stable single frequency (according to the frequency meter reading) signal was established in the oscillator circuit. The oscillator frequency and defect mode Q are in the good agreement with the defect mode observed in transmission experiments for corresponding defect size.

To verify the technique for high Q measurements using the PIN diode switch, the closed circuit oscillator was set up for the PBG structure with copper supporting plates at room temperature. The energy decay for this setup is presented in 4.3.6. It corresponds to a Q of 2300. This value is in the good agreement with the other Q values received by different techniques, and provides good support for the measurements presented here.
<01> Transmission Spectrum, Structure N1
032" Defect 3 lattice from Input and Output Coupling Ports, T=4.2 K.

Figure 4.3.1
<01> Transmission Spectrum, Structure N2, 0.044" Defect, 3 Lattice Spaces from Input and Output Ports, T = 4.2 K

Figure 4.3.2
<01> Transmission Spectrum, Structure N2, No Defect, 6 Lattice Space Separation between Coupling Ports

Figure 4.3.3
Defect Mode vs Defect Size
Niobium Supporting Plates, T=4.2 K

![Graph showing resonance frequency vs defect size with solid and open symbols for two different structures.]

Open Symbols = Sapphire Structure N1
Solid Symbols = Sapphire Structure N2

Figure 4.3.4
Microwave Energy vs. Time Showing Characteristic Switching Time for PIN Diode

PBG Resonator Energy vs. Time after Switching off Incoming Power. Present Decay Time for 0.040” Defect Corresponds to Q=125000

Figure 4.3.5
PBG Resonator (Copper Supporting Plates at the Room Temperature) Energy vs. Time after Switching off Incoming Power. Present Decay Time for 0.024” Defect Corresponds to Q=2300

Figure 4.3.6
4.3.2 REVISING THE PBG STRUCTURE, DEFECT GEOMETRY, AND CONSTRUCTION.

To improve Q of resonator several criteria have been considered and the following steps have been accomplished.

The PBG sapphire structure and defects have been revised. We suspected that the sapphire structure could still be contaminated as a result of the ultrasonic drilling, although it was cleaned. The Q of a resonator, in this case, could be limited due to dielectric losses. PBG dielectric structure and defects have been thoroughly cleaned in series of organic solutions and then checked and photographed under the microscope (see Figures 3.1.6 and 3.1.7). However, dielectric structure cleaning did not result in Q improvement.

The niobium supporting plate surfaces were rough after machining. We believe the Q was limited due to a number of reasons such as flux trapping, larger effective surface, etc. Niobium supporting plates were polished with a sand paper and alumina polish. The surface relief was removed. However, due to the edges on the bottom plate it was difficult to maintain surface flatness. We believe that the niobium supporting plate surface became slightly concave after polishing, as depicted in Figure 4.3.7. The polished plates were tested with 0.036" defect. They showed the presence of several small resonances in the 36-38 GHz frequency range with the main resonance at 37.8 GHz. Adjusting the phase shifter isolates the oscillator to a single frequency and eliminates the other frequencies. The decay time for the main resonance is presented in the Figure 4.3.8. It corresponds to the Q of $1.1 \times 10^6$. The other resonances had Q 2 ~ 6 times smaller than the main resonance. The examples of the time constant of energy decay for these resonances are shown in Figure 4.3.9.

To investigate the nature of the multiple resonances, the defect was removed from the dielectric wafer, and the closed circuit oscillator was set up with the PBG structure at 4.2 K with coupling port separation of 6 lattice spaces. The main high Q resonance were not observed. However, the other lower Q resonances remained in the spectrum.

We believe that uneven surfaces of supporting plates form resonance cavities, which in case of niobium give strong resonances. This assumption is confirmed by the data received from the HTS composite supporting plate (copper-copper supporting plates) testing described in the following chapters.
Schematic Presentation of Niobium Supporting Plates after Polishing

up to 0.010" ~ 0.015"

Figure 4.3.7
PBG Resonator (Niobium Supporting Plates at 4.2 K) Energy vs. Time after Switching off Incoming Power. Present Decay Time for 0.036” Defect Corresponds to $Q=1.1 \times 10^6$

Figure 4.3.8
Example of Resonances Formed after Polishing Niobium Supporting Plates. Energy vs. Time after Switching off the Incoming Power to the PBG Structure with no Defect.

Decay Time Corresponds to $Q=480000$.

![Graph](image)

Decay Time Corresponds to $Q=240000$.

![Graph](image)

Figure 4.3.9
4.3.3 ULTRA STABLE PBG OSCILLATOR OPERATING AT 4.2 K WITH LOADED Q OF $10^6$

One of the important results of this project is that we have built a closed circuit oscillator based on the PBG resonator with niobium supporting plates operating at 4.2 K. The loaded Q of the resonator is $1 \times 10^6 \sim 1.1 \times 10^6$ (see Figure 4.3.8). As the defect mode is not coupled to match according to the design (we were trying to avoid overcoupling, the defect mode is undercoupled in our case), we are not specifying the exact real Q value. Although, the real Q is in the range of $1.1 \times 10^6 \sim 2.2 \times 10^6$. As we mentioned above, after adjusting the phase shifter a very stable signal is established in the oscillator. Avoiding really rough mechanical vibration, the oscillator is stable for hours. We observed it to be stable for at least 12 hours. To confirm that the PBG oscillator with Q of $10^6$ at 4.2 K is a consistent phenomenon, several different sizes of defect mode were tested. Figure 4.3.10 shows the energy decay vs. time for 0.044” defect.

We believe that the main energy dissipation mechanism in the PBG resonator with niobium plates is still due to surface resistance of the plates. The Q of the PBG resonator with niobium supporting plates could be improved if the plate’s surfaces were better treated. Due to the niobium softness, it is very difficult to machine this metal. Even though surface relief were removed and plates had metal shine after they had been polished, the polishing material could be introduced into the niobium surface (due to its softness) causing its contamination and increase in surface resistance. Different surface preparation techniques for microwave applications were described in [11-13]: chemical polishing, electropolishing, anodic oxidation (and then stripping the oxide), ultrahigh vacuum annealing. All above techniques improve surface condition resulting in decrease surface resistance.

The prospect of increasing Q of the PBG resonator with niobium supporting plates further is likely with more attention to the surface preparation.
Oscillator on the Base of PBG Resonator with Niobium Supporting Plates at 4.2 K.
Energy vs. Time after Switching off Incoming Power.
0.044” Defect, Q=1×10^6

Figure 4.3.10
4.4 PHOTONIC BAND GAP STRUCTURE WITH HTS COMPOSITE SUPPORTING PLATES

4.4.1 DEFECT MODE EVALUATION WITH COPPER-COPPER COMPOSITE SUPPORTING PLATES

The design for HTS composite plates are presented in Figure 3.2.5. As all previously tested PBG structures had supporting plates manufactured from a single piece of a bulk metal, the plate’s surfaces were continuous and fairly flat. A question is raised of how the discontinuous surface of composite plates will impact the defect mode. For this purpose the HTS inserts (HTS film on the sapphire substrate, as shown in Figure 3.2.6) in the composite structure were substituted with the copper inserts. A series of experiments were conducted to compare the PBG with copper-copper composite supporting plates to the PBG with solid copper supporting plates.

The PBG structure with no defect has been tested in reflection (experimental setup as shown in Figure 3.4.1 (c)) and as a part of a closed circuit oscillator (experimental setup as shown in Figure 3.4.2). A typical reflection spectrum for PBG structure with copper plates and with no defect is presented in Figure 4.4.1. Reflected power oscillations with no resonances are observed. In contrast, using the copper-copper supporting plates resulted in multiple small resonances in the 37 ~ 40 GHz frequency range (see reflection spectrum in Figure 4.4.2). The results received from the closed circuit oscillator tests support the transmission data. There is no power in the oscillator circuit with the PBG structure with copper supporting plates. However, we have observed a resonance at 37.75 GHz in the oscillator with the PBG with copper-copper composite supporting plates. We believe that the observed resonances, analogous to the niobium polished plates, are due to the non-flat surface of the plates. It was really problematic to machine 0.020” thick copper inserts while minimizing deformations to provide flat surface for composite plates.

Transmission and reflection experiments conducted for the PBG structure with solid copper plates for different defect size are described in Chapter 4.2. Two defect modes (around 35 and 38 GHz) for each defect size were observed. The PBG structure with copper supporting plates has been tested as a part of closed circuit oscillator for different defect size. A single resonance corresponding to the higher defect mode was excited in the oscillator circuit.

Transmission and reflection experiments have been conducted for the PBG structure with copper-copper composed plates for different defect size. A typical reflection spectrum is shown in Figure 4.4.3 for the PBG structure with 0.032” defect. Two distinctive resonances at about 34.8 and 38.5 GHz are seen in the reflection spectrum for 0.032” defect. However, the resonance at 38.5 GHz is in the
frequency range associated with uneven supporting plate surface resonances. Reassembling the PBG structure causes changes in the reflection spectrum. It is not clear if the resonance at 38.5 GHz is associated with a defect or it is due to the uneven surface of the composite supporting plates. The closed circuit oscillator containing the PBG structure with a defect and copper-copper composed supporting plates can be excited at several frequencies around 35 and 38 GHz.

Two possible explanations can be suggested for the observed phenomena:

It may be due to the discontinuous and non-flat surface of the supporting plates coupling to a defect changes causing a defect mode frequency shift. The main defect mode (referred in previous chapters as higher defect mode) shifts to the lower frequency range and can be excited now in the oscillator circuit. The near 38 GHz resonance is associated with the uneven surface of supporting plates.

Or, the discontinuous and non-flat surface does not change the coupling to a defect. Instead, it creates resonances in the 37 ~ 40 GHz frequency range which coexist with defect modes at 35 and 38 GHz already observed for the PBG structure with solid copper plates. However, unlike defect modes for the PBG with copper plates, both defect modes for the PBG with composed plates can be excited in the oscillator circuit.
Reflection from Coupling Port
PBG Structure with No Defect, Copper Plates

Figure 4.4.1
Reflection Spectrum for Antenna Type Coupling Port. PBG Structure with no Defect, Copper-copper Composed Supporting Plates

Figure 4.4.2
Reflection Spectrum, 0.032" Defect, Copper-copper Composed Plates

Figure 4.4.3
4.4.2 DEFECT MODE EVALUATION WITH HTS-COPPER COMPOSITE SUPPORTING PLATES

The PBG structure with HTS composite supporting plates and defect was tested in reflection, transmission, and as a part of a closed circuit oscillator. There was no defect mode observed in the frequency range of 33 ~ 40 GHz. As a defect mode existed for all previously tested conductive supporting plates, the question of YBCO film conductivity raised.

To check the HTS film on sapphire substrate was sandwiched between two inductive coils. An AC signal was supplied to one of the coils and the output from the other due to magnetic induction was measured. Upon cooling the YBCO film, it was expected to receive sharp decrease in the output signal as the film goes though the superconducting transition. However, no change in mutual inductance between coils was observed over the 10 kHz ~ 10 MHz frequency range while cooling YBCO down to 4.2 K. To check the coil sensitivity sapphire substrate and copper plate have been sandwiched and tested analogously to YBCO film. The second coil output changes by a factor of several when a copper plate is inserted. Upon cooling the copper plate from room temperature to 77 K, the mutual inductance between coils changes 4 ~ 5 times in the kHz frequency range.

The decision has been made to purchase new superconducting plates. Single sided epitaxial YBCO film on LaAlO$_3$ substrate with $T_c > 87$ K, $\Delta T_c < 1$ K, $R_s < 0.8$ m$\Omega$ @ 77 K @ 10 GHz will be delivered by Neocera, Inc before January 2, 1997.

YBCO films on LaAlO$_3$ substrate were delivered by Neocera, and then they were tested in the PBG resonator setup. Unfortunately, while assembling the PBG resonator (the procedure was completed in the flow bench) the YBCO films became covered with spots, and, again, no resonance mode was observed.
5. POTENTIAL COMMERCIAL APPLICATION

5.1 POTENTIAL APPLICATION OF PBG OSCILLATOR-RESONATOR AND CRYOGENIC MICROWAVE FACILITY

As we reported previously there is significant potential demand for monofrequency high quality factor low phase noise sources. They are desired for use as local oscillators in microwave communication links. This is especially true for systems employing direct-sequence spread-spectrum modulation (i.e. code division multiplexing). Low loss, sharp-skirted filter banks are desired for frequency-division multiplexing and power combining.

System performance of a Doppler radar, or other applications requiring very small shifts close in to the carrier, is critically dependable upon the phase noise of the reference source. An improvement of, for example, 10 dB in the low frequency phase noise would result in dramatic improvements in system performance.

The Defense Department was the first user of spread-spectrum modulation. A major drawback of spread spectrum modulation, however, is the time required to resynchronize the transmitter and receiver. A low phase-noise oscillator can help by greatly reducing the correlation search volume for re-establishment of a link. The DOD’s needs for this technology might serve to aid the insertion of these devices into future commercial systems.

Multi-channel filter banks are very useful for signal sorting or presorting. These types of operations are widely used in signal-analysis equipment which gathers intelligence, issues warning of radar threat, or generates electronic countermeasures. The PBG structures can play significant role in this field. We have been able to place several discrete frequencies within the same band gap in one device, and also can expect to design a single configuration that has several bandgaps, each with its own defect resonance.

The benefits offered by superconductivity in monofrequency low phase noise resonator technology has already been demonstrated by their superior performance at the system and subsystem levels. We have analyzed recent publications on microwave low phase noise high Q resonators-oscillators. Many of them contained results on oscillators using sapphire “whispering gallery” mode disk dielectric resonators operating in the 9 ~ 10 GHz frequency range. The best reported in [14-16] unloaded quality factors were 4x10⁹ ~ 8x10⁹ at 4.2 and 1.6 K, respectively, and 3x10⁵ ~ 5x10⁸ at the liquid nitrogen temperatures, achieving sometimes up to 5x10⁷. A loaded Q of 59000 at 36.5 GHz and 77 K obtained from a sapphire disk resonator shielded by HTS ground planes has been reported in [17].
DuPont Superconductivity produces HTS dielectric cavity resonators in the 3 - 40 GHz frequency range. The unloaded Q at 77 K are $3 \times 10^6$ at 5.5 GHz, $1 \times 10^6$ at 10 GHz, expected Q at 40 GHz is approximately $1 \sim 2 \times 10^5$. The purchase price for the DuPont's resonators is in the $50,000 range.

We have proved principles of operating the resonators based on PBG. At the present stage, they already have shown Q values comparable to the contemporary state-of-art dielectric cavity resonators. We have identified the need for careful surface preparation to increase Q for the PBG resonator with niobium supporting plates. Dielectric cavity resonators are sensitive to the microscopic properties of the dielectric such as temperature stability, vibration, etc. Generally speaking, PBG resonators are sensitive to the macroscopic properties of a periodic dielectric structure (PBG structure). The PBG structure is quite rigid mechanically. The PBG resonator is a true single frequency resonator, while all possible harmonics are present in the dielectric cavity resonators. Considering the above arguments, the resonators based on PBG offer performance advantages and are less expensive than other superconducting resonators.

We would like also to mention that valuable experience has been acquired in designing the cryogenic microwave facilities. The designed cryogenic system by itself is sufficiently ubiquitous that it can be used as a platform for a variety of microwave experiments, both transmission and reflection, and additionally for testing microwave components at low temperature in the 26-40 GHz frequency range. Through our work on this project, we have discovered other additional demand for low temperature microwave performance testing from a number of contacts.
5.2 PBG FILTER-OSCILLATOR COST ANALYSIS FOR MANUFACTURE AND SALE

We present below (see Table 5.1.1) the approximate cost of manufacturing the prototype oscillators based on PBG resonators with niobium supporting plates operating at 4.2 K and with HTS supporting plates operating at 77 K. We also present the estimated cost of manufacturing the oscillators in quantity.

**Table 5.1.1**

<table>
<thead>
<tr>
<th>Plates</th>
<th>Niobium Supporting Plate</th>
<th>HTS Supporting Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operated at LHe Temperatures</td>
<td>Operated at LN$_2$</td>
</tr>
<tr>
<td></td>
<td>Prototype Cost ($)</td>
<td>Production Cost ($)</td>
</tr>
<tr>
<td><strong>PBG structure and cryogenic system cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSI Hemlite sapphire 4” diameter blank</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>Drilling holes in sapphire</td>
<td>1200</td>
<td>850</td>
</tr>
<tr>
<td>Machining the defects (5 different size, 2 of each)</td>
<td>930</td>
<td>0</td>
</tr>
<tr>
<td>Niobium for supporting plates</td>
<td>550</td>
<td>300</td>
</tr>
<tr>
<td>Machining the niobium supporting plates</td>
<td>495</td>
<td>360</td>
</tr>
<tr>
<td>Niobium supporting plate surface treatment</td>
<td>1300</td>
<td>350</td>
</tr>
<tr>
<td>Machining the copper bases for HTS composed supporting plates</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HTS films</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waveguide</td>
<td>320</td>
<td>280</td>
</tr>
<tr>
<td>Waveguide silverplating</td>
<td>675</td>
<td>450</td>
</tr>
<tr>
<td>Coaxial cable</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Waveguide to coax adapters</td>
<td>1100</td>
<td>900</td>
</tr>
<tr>
<td><strong>Glass beads for coupling ports</strong></td>
<td></td>
<td></td>
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<tr>
<td>Flanges for a waveguide</td>
<td>110</td>
<td>90</td>
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<tr>
<td>Connectors for coax</td>
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<td>60</td>
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<tr>
<td>Thermometer</td>
<td>100</td>
<td>100</td>
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<tr>
<td>Item</td>
<td>1260</td>
<td>1080</td>
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<td>-----------------------------------------------------------</td>
<td>------</td>
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</tr>
<tr>
<td>Valves</td>
<td>25</td>
<td>20</td>
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<tr>
<td>Machining parts for cryogenic system and welding</td>
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<td></td>
</tr>
<tr>
<td>Liquid helium dewar</td>
<td>3200</td>
<td>2000</td>
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<tr>
<td>Cryogenic system assembly and test</td>
<td>480</td>
<td>450</td>
</tr>
<tr>
<td>Miscellanies</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>$12,703</td>
<td>$7,858</td>
</tr>
<tr>
<td><strong>Oscillator circuit cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplifier</td>
<td>3450</td>
<td>2900</td>
</tr>
<tr>
<td>Phase shifter</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>Attenuator</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Isolator</td>
<td>100</td>
<td>100</td>
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<tr>
<td>Waveguide sections</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>10 dB directional coupler</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>E- and H-bends</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>Power supply</td>
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<td>80</td>
</tr>
<tr>
<td>Total</td>
<td>$5,380</td>
<td>$4,140</td>
</tr>
<tr>
<td>System test</td>
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<td>550</td>
</tr>
<tr>
<td><strong>Total oscillator cost</strong></td>
<td>$18,683</td>
<td>$12,548</td>
</tr>
</tbody>
</table>
6. CONCLUSIONS

Based on Phase 1 theoretical calculations and theoretical investigation of hybrid mode, the design of the K-band resonator was completed. The following parameters of the two-dimensional sapphire square lattice were selected:

<table>
<thead>
<tr>
<th>Lattice material</th>
<th>Sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline orientation</td>
<td>c-axis perp. to 2-D PBG lattice</td>
</tr>
<tr>
<td>Dielectric constant (c-axis)</td>
<td>11.56 ( @ 300 K)</td>
</tr>
<tr>
<td>PBG lattice diameter</td>
<td>4”</td>
</tr>
<tr>
<td>Lattice thickness</td>
<td>0.080”</td>
</tr>
<tr>
<td>Lattice spacing</td>
<td>0.084”</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>0.076”</td>
</tr>
<tr>
<td>Minimum web thickness</td>
<td>0.008”</td>
</tr>
<tr>
<td>Center freq. (Design)</td>
<td>35.11 GHz</td>
</tr>
<tr>
<td>Center freq. (measured)</td>
<td>approx. 37 GHz</td>
</tr>
<tr>
<td>Band gap (Design)</td>
<td>4.4 GHz</td>
</tr>
<tr>
<td>Band gap (measured)</td>
<td>&gt;3 GHz</td>
</tr>
</tbody>
</table>

The measured center frequency and band gap are based direct in-plane transmission measurements at room temperature. For the PBG structures it was found there exists a band gap with a lower edge starting at approximately 35 ~ 36 GHz and reaching 39.5 GHz or higher, the upper limit of our microwave source. The experimentally defined photonic band gap was shifted by at least 1.5 GHz towards higher frequencies as compared to the theoretically calculated results. It is concluded that this shift is due to the number of oversized holes in PBG structures and, correspondingly, its lower average dielectric constants.

Introducing a defect (a sapphire cylinder with the O.D. to fit a hole in the periodic dielectric structure and variable I.D.) creates one or two resonance modes in the observed frequency range depending upon the temperature and the type of supporting plate. The defect mode frequency is observed to increase with the increase in defect I.D. By varying the defect size, it is possible to find a defect mode lying near the middle of the band gap (and therefore, a localized high Q mode), and with the energy density distribution as is predicted in the theoretical calculations (see Figure 1.2.5).

For the K-band resonator with copper supporting plates at room temperature, there were two defect modes, one each near 35 and 38 GHz. However, it was shown that the lower frequency defect mode is near the band edge and is not localized mode. The Q of higher frequency localized mode at room temperature was in the range of
900 ~ 2000 magnitude. The observed Q for the Cu plate structure at 77 K was in the range of 4000 ~ 12000, due to lower resistive losses in copper at 77K.

Antenna-type coupling ports were used to couple microwave energy into the PBG resonator. Based on a number of reflection and transmission experiments, and varying the coupling conductor protruding length and coupling port separations, it was decided to use standard size glass beads manufactured by Wiltron working in the 26-40 GHz frequency range where the coupling strength could be changed by varying the separation between the coupling port and the defect. It was desired to keep the insertion losses of the structure under about 10 dB while simultaneously avoiding strong perturbation due to the coupling (a slightly undercoupled operative mode was targeted). Operating at cryogenic temperatures it was determined that a near optimal separation between coupling ports of 6 lattice spaces in <01> direction of dielectric periodic structure was needed.

The cryogenic system for operating at liquid helium temperatures was built. This system by itself is sufficiently ubiquitous that it can be used as a platform for a variety of microwave experiments, both transmission and reflection.

The PBG resonator with superconducting niobium plates operating at 4.2 K was also constructed. The closed-circuit oscillator based on the PBG resonator has been constructed. A very stable single frequency corresponding to the introduced defect mode could be excited in the oscillator circuit. The Q was evaluated through the time constant of energy decay stored in the resonator. The loaded Q of the PBG resonator-oscillator with superconducting niobium plates was 1.1x10^6. The coax microwave energy was somewhat undercoupled to defect mode, it is expected that the unloaded Q should be in the 1.1x10^6 ~ 2.2x10^6 range. We have concluded that the main energy dissipation mechanism in the PBG resonator with niobium plates is due to surface resistance of the plates. Better machining in combination with the surface treatments such as chemical polishing, electropolishing, anodic oxidation (and then stripping the oxide), ultrahigh vacuum annealing can result in substantial Q increase.

The results at 4K demonstrated a number of things. Firstly, the overall viability of a PBG structure in the Q band was demonstrated. The mode is sufficiently localized within the overall diameter of the PBG structure to support a Q in excess of 10^6. The ability of the system to attain such a high Q also helped to remove doubts as to other possible limitations in measuring the Q of the anticipated move to HTS films at 77K. The instrumentation, the coupling load, dielectric losses, the detector and switching diodes were all confirmed not to be limitations on system performance.

A PBG resonator with HTS supporting plates was designed and built as follows: a YBCO film was deposited on a sapphire or LaAlO3 substrate of 2.0” diameter, and then inserted into the copper plate. To demonstrate that the defect mode exists in
the resonator with composed (discontinuous) surfaces, 2.0” diameter copper plates (instead of YBCO film on a substrate) were inserted into the copper supporting plates and tested. However, we could not observe a defect mode with YBCO composed supporting plates.

There is a demand for high Q low phase noise microwave resonators-oscillators. The PBG resonator has already shown Q values comparable to the contemporary state-of-art dielectric cavity resonators. We have identified the need for careful surface preparation to increase Q for the PBG resonator with niobium supporting plates. The advantages of the PBG resonator to dielectric cavity resonators were identified as the following: while dielectric cavity resonators are sensitive to the microscopic properties of the dielectrics such as temperature stability, vibration, etc., PBG resonators are sensitive to the macroscopic properties of a periodic dielectric structure (PBG structure). The PBG structure is quite rigid mechanically. The PBG resonator is a true single frequency resonator, while all possible harmonics are present in the dielectric cavity resonators. The cost analysis for the PBG filter-oscillator manufacture showed that it can be priced competitively.
APPENDIX A. ASSEMBLING THE PBG RESONATOR AND OPERATING THE CRYOGENIC FACILITIES

1. PBG resonator including periodic dielectric structure, defect and coupling ports should be assembled together.
2. Prepare the cryogenic insert for mounting the PBG resonator as shown in Figure A.1.
3. Secure the PBG resonator on the mounting brackets, connect the coaxial cables to the input and output coupling ports, attach copper thermal connectors to the supporting plates, place a thermometer on the supporting plate surface for monitoring the temperature if desired (see Figure A.2).
4. Place indium wire in the vacuum can groove and place the resonator in the vacuum can. To provide required pressure for quality vacuum seal place the specially manufactured metal plate as shown in Figure A.3 on the top the vacuum can. Torque the nuts using a torque wrench up to 50 - 60 lbs - in.
5. Evacuate air from the vacuum can through the vacuum valve on the top of the probe. Remove the metal plate from the vacuum can top. The cryostat as is shown in Figure A.4 can be placed in the dewar for cooling down to the cryogenic temperatures.
6. The safety precautions for cryogenic liquid handling should be undertaken when transferring liquid helium to cool down the system.
Cryogenic Insert for Mounting the PBG Resonator
The PBG Resonator Incorporated into the Cryogenic Insert
Figure A.2
Figure A.4
LIST OF REFERENCES


17. Negrete G.V. An ultra-low-noise millimeter-wave oscillator using a sapphire disk resonator and high-temperature superconductor ground planes. Microwave and Optical Tech. Let. V.6, N13, 1993 (758-762)