Photonic band gap structures for millimeter-wave traveling wave tubes

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ABSTRACT

We propose to use photonic band gap (PBG) structures for constructing traveling wave tubes (TWTs) at 100 GHz, a completely novel approach. Using a PBG fiber allows us to create an all-dielectric slow-wave structure with very large band width and low losses in the mm-wave regime, compared to TWTs made out of metals. Additional capabilities such as mode selectivity are also achievable. We designed two 100 GHz pencil beam PBG TWTs using Ansoft's HFSS, 3D electromagnetic simulation software for high frequency applications. The first design is a periodic array of vacuum rods in a dielectric matrix, with a smaller vacuum rod forming the line defect. A fiber drawing procedure is being utilized to construct this design out of fused silica. The second structure is a periodic array of dielectric rods in a vacuum matrix, surrounding a thick hollow dielectric tube that accommodates the electron beam. This model is being fabricated out of silicon by means of high-pressure laser chemical vapor deposition (HP-LCVD), a versatile approach to synthesize fibers from the vapor phase. Additionally, a scaled 10 GHz cold test made from alumina rods is being produced for design confirmation purposes, and a 100 GHz sheet beam PBG TWT is being investigated for even greater power generation.

Keywords: Photonic band gap (PBG) structures, photonic crystal (PC) fibers, millimeter-wave, traveling wave tube, vacuum electronics, fiber drawing, high-pressure laser chemical vapor deposition (HP-LCVD)

1. INTRODUCTION

Interest in millimeter-waves (W-band) has increased in recent years due to applications in environmental monitoring and arms-control treaty verification[1,2]. Remote detection of airborne chemicals, such as chemical effluent from materials processing facilities, is non-intrusive and suitable for examining large areas, compared to the alternative point detection or sampling techniques. Millimeter-waves are advantageous to use for remote spectroscopy because they are less susceptible to clouds, dust, rain and poor visibility conditions, through which optical measurements are impossible. A wide bandwidth source (five percent or better), is a requisite in order to attain spectra broad enough for reliable chemical identification. Before mm-wave sensing can be practical, a high-power radiation source must be developed, as no commercial device currently exists that can deliver 1kW of mm-waves with wide bandwidth.

Traveling wave tubes (TWTs) are traditionally employed to generate high-power radiation, a technology that was developed in the mid-twentieth century for radar applications[3]. TWTs are non-resonant, periodic, slow-wave structures, typically made out of metal. An electron beam directed along the symmetry axis interacts with a traveling electromagnetic (EM) wave propagating in tandem. The EM wave is amplified as a result of the interaction. The efficiency of the device is dependent upon the material properties in the operational frequency range.

An alternative approach is to construct an all-dielectric TWT. We proposed to do this using photonic crystals[4], which are periodic structures of dielectric material. Analogous to the filtering of electrons traveling through a periodic potential in solid-state physics, certain frequencies of photons traveling through periodic dielectric media will be forbidden. The range of wavelengths that are prohibited is called a photonic band gap (PBG). One can engineer the location and width of the band gap by modifying the dimensions, namely the shape, size, and spacing, of the dielectric objects forming the structure.

As an example of a PBG structure, we can consider the design shown in Figure 1, a triangular array of dielectric rods with dimensions characterized by a and b, the rod radius and lattice spacing, respectively. One can modify these structural parameters in order to achieve a band gap, which can be tuned to frequencies of interest.

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Just as electronic states in semiconductors can be confined to defects, one can also confine photonic states. In the 2-dimensional case investigated here, a cylindrically symmetric defect can be created in a PBG fiber consisting of a triangular array of dielectric rods by removing one rod in the center and inserting a dielectric tube. The defect line along which the periodicity is broken will confine frequencies that lie in the photonic band gap. The modes concentrated in the defect tube are free to propagate down the fiber. Resultantly, the defect mode will interact efficiently with the electron beam, yielding a TWT.

In addition to being able to mitigate losses, there are further benefits to using dielectric PBG TWTs. First, PBG structures allow for mode selectivity. In conventional high-power TWTs, higher-order modes are excited that decrease efficiency when mode-selective operation is desired. Single-mode excitation is achievable in PBGs, since the frequencies within the band gap will be confined to the central defect and unwanted modes will be suppressed.

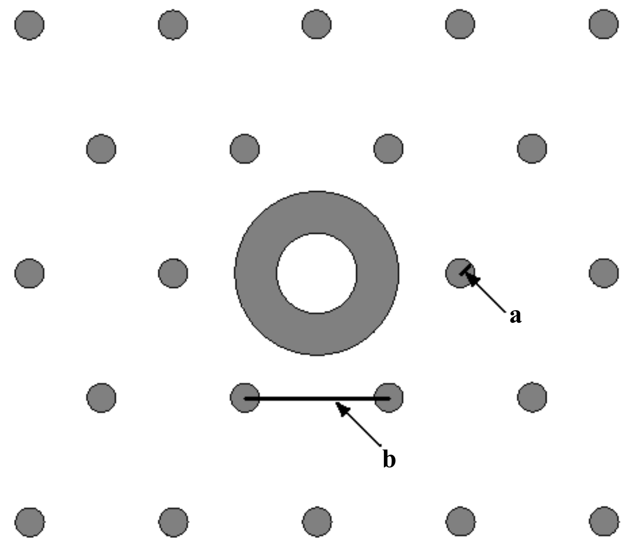

Figure 1: Cross-sectional structural image of a PBG fiber, demonstrating a cylindrical defect and the parameters *a* (rod radius) and *b* (lattice spacing). The white area is vacuum, and the grey is dielectric.

Second, by using dielectric materials, one can in principle achieve more than one hundred percent bandwidth. Dielectrics are intrinsically slow-wave; therefore, periodicity is not needed along the axial direction to slow the propagating EM radiation. This can be contrasted to periodic metal designs, in which the bandwidth is limited to 10%. Third, TWTs based on dielectric structures will have a linear dispersion relation, which affords great beam-to-wave interaction, permitting high instantaneous bandwidth.

Furthermore, fabrication of dielectric designs has the potential to be much cheaper, easier, and faster, enhancing the commercial transferability of this technology. Traditional machining is troublesome at 100 GHz and impossible at 1 THz. Scientists have had to resort to more expensive methods such as deep etch X-ray lithography: lithographie, galvanoformung, abformung (LIGA) to fabricate metal mm-wave TWT designs[5,6]. Simplified approaches for building dielectric TWTs, such as fiber drawing, can be used to attain sub-millimeter structural dimensions at a fraction of the time and cost.

We discuss here the design and development of three all-dielectric PBG TWTs and a scaled model for a 10 GHz cold test. The first two are engineered to operate at a frequency of 100GHz with a standard pencil beam electron source. The third design has a flat, linear defect to accommodate a sheet beam, which will also be operated at 100 GHz. Fabrication methods are discussed.

2. DESIGN AND FABRICATION OF PBG TWT STRUCTURES

2.1 Fiber-drawn structure

Figures 2 and 3 exhibit our first 100 GHz design. Both images are of a cross-sectional slice of fiber which extends axially out of the plane of the paper. Figure 2 shows the geometry of the PBG TWT structure, where the light grey regions represent vacuum, and the navy regions represent dielectric. Dimensions are displayed in Table 1.

We determined confined modes of our PBG designs using Ansoft's High Frequency Structure Simulator (HFSS)[7], three-dimensional electromagnetic simulation software for high frequency applications. HFSS was utilized to generate the plot of the magnitude of the axial electric field for the desired operating mode. The plot is superimposed on the structural image (Figure 3), in which the red color indicates a maximum field magnitude. The hole radius and lattice spacing (*a* and *b*, respectively), in addition to the relative defect size, were chosen to optimize the operating frequency of the traveling wave tube.

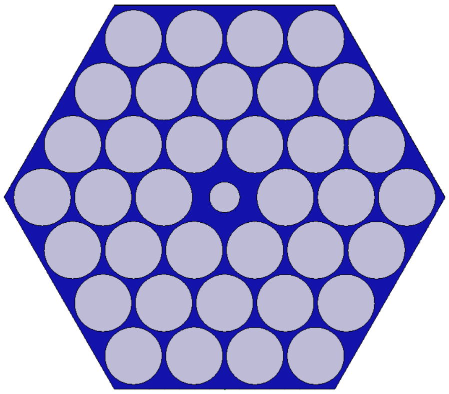

Figure 2: Cross-sectional drawing of a PBG structure designed for a pencil beam TWT (Navy: silicon, light grey: vacuum).

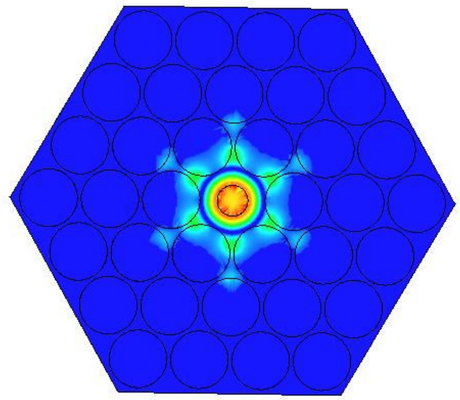

Figure 3: Magnitude of the axial component of the electric field for the operating TWT mode, computed with HFSS.

Table 1: Design dimensions of first prototype 100 GHz PBG TWT structure.

Lattice spacing b	0.81 mm
Hole radius a	0.38 mm
a/b	0.47
Defect radius	0.20 mm
Freq. (TM_{01})	99.3 GHz

Fiber drawing, the traditional means of producing optical fibers out of dielectric materials such as fused silica and other glasses, is being utilized for our first 100 GHz pencil beam design. A pre-form is made by stacking dielectric tubes and rods into a sheaf, creating the desired cross-sectional array of air columns. It is then heated to the material's softening temperature and drawn to a smaller diameter, illustrated in Figure 4. Standard fused silica, ubiquitous in optical fiber research, was chosen for our design. Fused silica has an intermediate dielectric permittivity (3.8[8]) and low losses at 100 GHz. A structure length of several inches will be easily attainable.

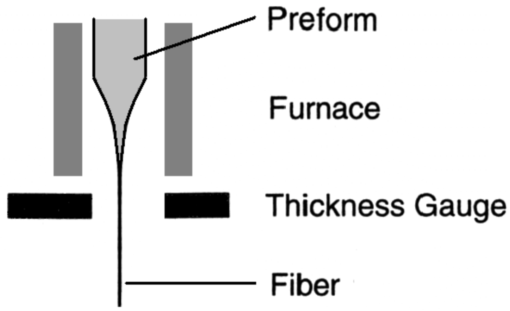

Figure 4: Schematic of the fiber drawing procedure.[9]

Novel materials, such as chalcogenide glasses, were also explored before finally selecting fused silica; however, relative dielectric permittivity and loss tangent characterization is incomplete in the 100 GHz frequency regime for most commercial materials. Although the real permittivity varies a smaller amount, loss tangents are extremely frequency dependent[10], eliminating the possibility of using data acquired in alternate bands of interest, such as terahertz. We are in the process of developing an experimental set-up for millimeter-wave materials characterization. This will allow us to take our own measurements of dielectric constants and loss tangents of materials previously not well characterized, so that novel materials can be seriously considered for future designs.

2.2 High-pressure laser chemical vapor deposition structure

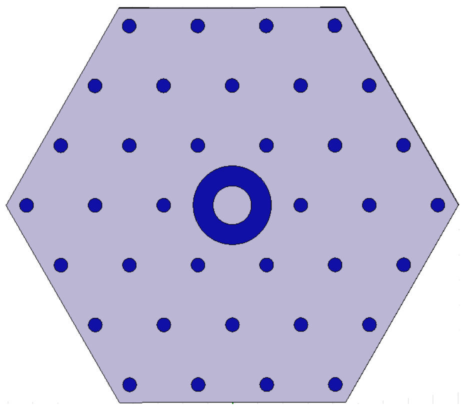

Figure 5: Cross-sectional drawing of a PBG structure designed for a pencil beam TWT (Navy: silicon, light grey: vacuum).

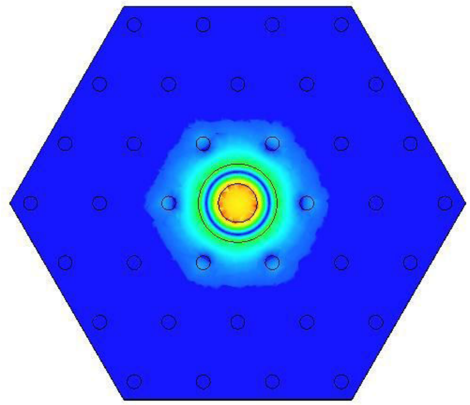

Figure 6: Magnitude of the axial component of the electric field for the operating TWT mode, computed with HFSS.

A second finalized 100 GHz design is shown in Figures 5 and 6, which consists of an array of fibers surrounding a central defect tube. Both images are again of a cross-sectional slice of fiber which extends axially out of the plane of the paper. Figure 5 shows the geometry of the PBG TWT, whose dimensions can be found in Table 2. Light grey regions represent vacuum, and navy regions represent dielectric. Figure 6 displays the HFSS-generated plot of the magnitude of the axial electric field for the desired operating mode, which is superimposed on the structural image. Red indicates a maximum field magnitude.

Table 2: Design dimensions of second prototype 100GHz PBG TWT structure.

Lattice spacing b	1.37 mm
Rod radius a	0.14 mm
a/b	0.10
Defect ID/OD	0.77 mm/1.56 mm
Freq. (TM_{01})	100.6 GHz

Alternative means of fabrication were considered for the second 100 GHz pencil beam design. Millimeter-wave structures present many challenges due to their awkward size and shape. The sub-millimeter dimensions and high aspect ratio render one-inch dielectric fibers impossible to build by traditional machining methods. Additionally, the features are too large and elongated to be effectively made by established micro electrical mechanical systems technologies. After investigating novel approaches, we determined that high-pressure laser chemical vapor deposition (HP-LCVD) is a viable method.

In the HP-LCVD method, a laser-heated surface initiates molecular decomposition of precursor gas and subsequent reaction to form a solid deposit of material on a substrate. A fiber then evolves from the surface, emerging in the direction of the laser beam (Figure 7). The smaller rods that constitute the PBG cladding will be grown by this method on a conducting surface that will double as structural support. The central tube will be purchased commercially due to its larger size. The complete structure length will be approximately one inch.

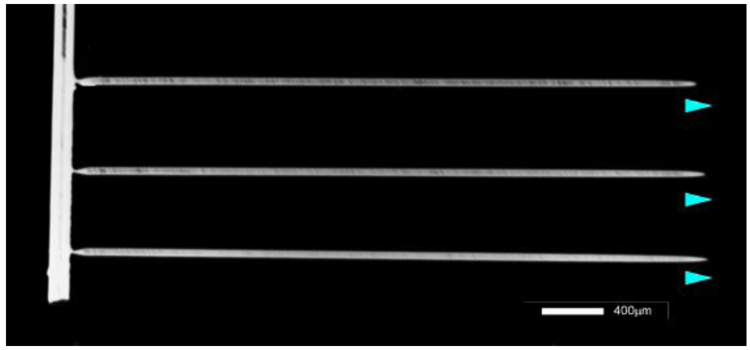

Figure 7: Freestanding carbon fibers grown by HP-LCVD[11].

Other dielectric materials were explored for the second 100 GHz pencil beam design. For maximized efficiency, we sought materials with low losses at 100 GHz, quantified by a loss tangent of less than 0.001, and a relatively high dielectric permittivity, between ten and twenty. Silicon was ultimately decided for the HP-LCVD structure, which reasonably matched our criterion[8].

Background studies are currently being carried out to determine thermodynamics of fiber growth for a silicon CVD system, which will dictate the required concentration of precursor gas and applied laser power for the size of fibers we desire to produce. Once preliminary studies have been completed, this technique will be implemented to build our design.

HP-LCVD is a versatile technique for growing fibers because a wide range of precursor gases can be used to achieve fibers of a desired material and phase. However, there are significant limitations present, as well. The fiber length of HP-LCVD grown fibers is limited. We will most likely not be able to realize a design several inches long, which is more than attainable by using fiber drawing. Additionally, this design, without a continuous matrix of dielectric, will be considerably more delicate due to limited structural reinforcement. Supplementary metal supporting rods spanning the two endplates outside of the region of PBG cladding will hopefully serve to extend the lifetime of our fiber and mitigate damage caused by handling. Commercial transferability at this stage appears limited, but the potential impact of HP-LCVD in PBG and optical fiber research is noteworthy.

2.3 10 gigahertz cold test model

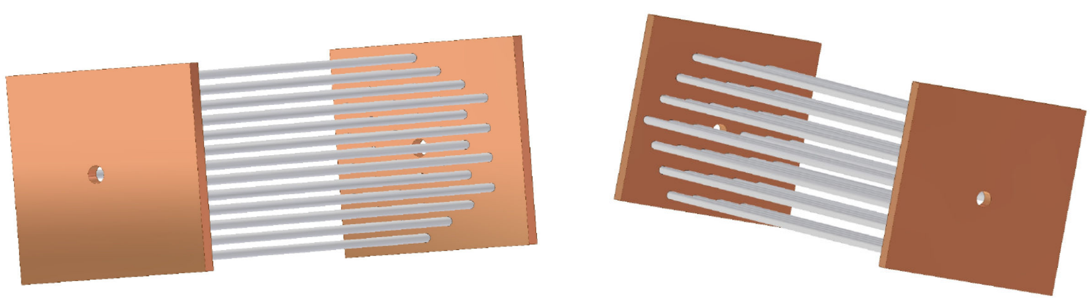

Figure 8: Structural design images of the 10GHz cold test model, made of alumina rods and copper endplates.

A 10 GHz cold test is also being constructed for design confirmation purposes. The design is scaled from the 100 GHz HP-LCVD structure, described in Section 2.2. Structural dimensions in the 10 GHz frequency range correspond to manageable features sizes, allowing for easy fabrication through conventional machining techniques. Figures 5 and 6 display the structural image and the superimposed magnitude of the axial electric field, respectively. The light grey regions represent vacuum, and the navy regions represent dielectric. Dimensions can be found in Table 3. Die cast alumina rods and the central defect tube will be purchased commercially and brazed to copper endplates to form the completed structure, modeled in Figure 8.

Table 3: Dimensions of scaled 10 GHz PBG TWT cold test structure.

Lattice spacing b	2/3”
Rod radius a	1/16”
a/b	3/32
Defect ID/OD	1/2", 7/8”
Freq. (TM_{01})	8.6 GHz

A HP8720C vector network analyzer will be used to cold test the 10 GHz model. However, a way of coupling power into and out of the device must first be formulated. How easy it is to couple power will dictate the usefulness of this type of design versus alternative PBG structures such as omnifibers[12], for which coupling power may be more easily realized.

2.4 100 gigahertz sheet beam design

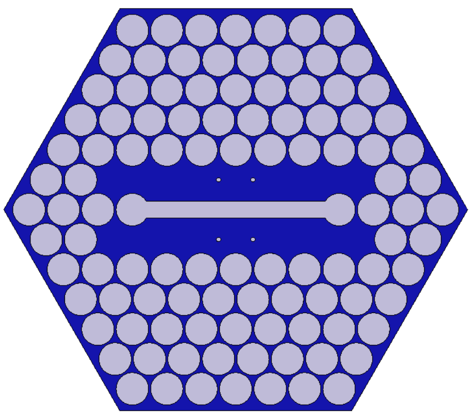

Figure 9: Cross-sectional drawing of a PBG structure designed for a sheet beam TWT (Navy: silicon, light grey: vacuum).

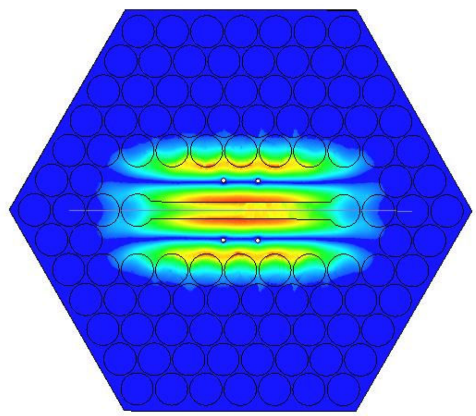

Figure 10: Magnitude of the axial component of the electric field for the operating TWT mode, computed with HFSS.

A100 GHz PBG TWT with a slit-shaped defect is being considered for a sheet electron beam. Interaction between a flat beam and the structure is more efficient than traditional pencil beams, due to the increased interaction interface. Therefore, sheet beam TWTs will have the capability to generate significantly more power. Figure 9 displays the fiber geometry, and Figure 10 is the generated plot of the magnitude of the axial electric field. Dimensions can be found in Table 4.

Table 4: Design dimensions of the 100GHz sheet beam PBG TWT structure.

Lattice spacing b	0.62 mm
Hole radius a	0.29 mm
a/b	0.47
Small hole radius	0.04 mm
Defect Width	0.31 mm
Freq. (TM_{01})	101.6 GHz

A constant electric field along the linear defect is desired for the most efficient power generation, which is maximized when every section of the sheet beam experiences an equivalent axial electric field. HFSS simulations were utilized to determine the field profile within the slit defect throughout the optimization procedure. By incorporating four small, additional vacuum holes between the defect and PBG cladding, we were able to attain a reasonably constant electric field within the beam cavity.

The development of a sheet beam is currently underway within our group[13,14], which will be used to test our prototype fiber, after design finalization and construction is complete. The sheet beam design is inherently more complex due to the breach in cylindrical symmetry that exists in the pencil beam structures. Possibilities for fabrication are being investigated.

3. CONCLUSIONS AND FUTURE WORK

In conclusion, the possibility of constructing 100 GHz TWTs entirely of dielectric materials was explored. Several TWT structures were proposed and modeled with HFSS to determine field patterns. We optimized our designs while investigating the means of fabrication. Potential means of construction of the TWT structures were considered and two fabrication methods were chosen. Properties of dielectric materials at 100 GHz were investigated to determine alternative materials, such as silicon, which will be used in the HP-LCVD design. Construction of two models is currently underway.

Future work includes the development of the power coupler, completion of the 10 GHz cold test model, fabrication of the two 100 GHz pencil beam design, and finalization and fabrication of the sheet beam fiber. Once the prototypes are fabricated, they will be tested with a network analyzer to validate HFSS simulations and then installed in a TWT test stand to demonstrate the generation of EM power.

4. ACKNOWLEDGEMENTS

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