DESIGN AND INITIAL TESTING OF OMNIGUIDE TRAVELING-WAVE TUBE STRUCTURES

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Abstract

We propose to use the photonic band gap (PBG) structures for the construction of a wide-band traveling-wave tube (TWT) at W-band. Interest in millimeter-waves has increased in recent years due to applications in communications, remote sensing, and basic research. The development of wide-band mm-wave TWT amplifiers is underway at Los Alamos National Laboratory. PBG TWT structures have great potential for very large bandwidth and linear dispersion. In addition, being cheap to fabricate, PBG structures enhance the commercial transferability of the W-band TWT technology. We employ an omniguide which is a one-dimensional version of a PBG structure representing a periodic system of concentric dielectric tubes as a slow-wave structure. A silica omniguide was designed to support the TM_{01}-like mode with a phase velocity matching the one of the 120keV electron beam. The structure was fabricated, cold-tested and will be installed in our laboratory for the hot test.

INTRODUCTION

Compact, efficient, high-bandwidth and high-power mm-wave sources are essential for many applications in secure communications, environmental monitoring, imaging, spectroscopy for remote sensing in nonproliferation, and basic research such as radio astronomy [1,2]. Spectroscopy missions in particular become more important at frequencies above 100 GHz, up to the THz range, and with bandwidths up to 30%. Until now, microwave vacuum tube technology has not scaled favorably to short wavelengths and wide bandwidths.

A wide-band mm-wave traveling-wave tube (TWT) amplifier development is underway at Los Alamos National Laboratory. We have already constructed and tested a 95 GHz TWT using a vane-loaded waveguide as a slow-wave structure and demonstrated 7% bandwidth in a cold test [3].

Now we propose to use the photonic band gap (PBG) structures [4] for constructing a TWT at 95 GHz, a completely novel approach.

OMNIGUIDE STRUCTURE FOR A TRAVELLING-WAVE TUBE

Traveling-wave tubes operate by co-propagating an electron beam and the electromagnetic wave inside a slow-wave structure, which is carefully designed to slow the wave to match the velocity of the electrons, typically about half of the speed of light. The electromagnetic power gets amplified by extracting the energy from the electron beam.

Commercial microwave tube amplifiers are available at frequencies up to only 100 GHz (W-band) and have to trade off maximum output power against bandwidth. In addition, the size of those devices scale as the wavelength of the microwaves they produce, and even at 100 GHz, TWTs are very small, and their fabrication becomes a serious challenge.

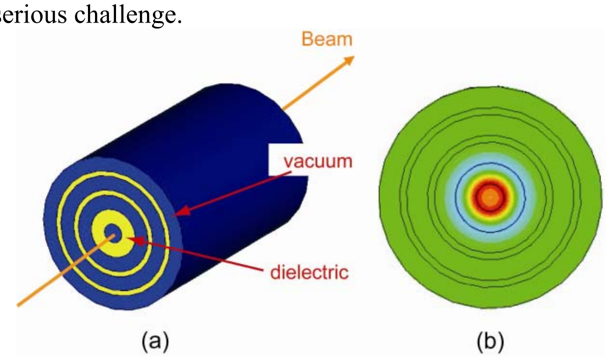

Figure 1: The schematic of an omniguide, the blue area is vacuum and the yellow area is dielectric (a); the longitudinal electric field magnitude in the TM01-like mode of an omniguide computed with Microwave Studio [6] (b).

We have developed a novel mm-wave traveling-wave tube architecture which is based on the PBG omniguide [5] structure (Figure 1(a)). An omniguide is an entirely dielectric structure which consists of concentric silica (SiO_2) tubes and serves to slow the electromagnetic wave to match the speed of the electron beam for efficient power generation. This TWT has a number of very important advantages over the conventional vane-loaded metallic devices. First, the simplicity of the design allows easy and cheap fabrication of the device with no novel and expensive manufacturing technologies (such as wire electro-discharge machining or even microfabrication) involved. Simplified approaches such as fiber drawing can be used to attain even sub-millimeter structural dimensions at a fraction of the time and cost. Second, the bandwidth of the omniguide TWT is only limited by the width of the photonic band gap in the omniguide, which for the prototype was designed larger than 20 per cent. Third, the dispersion of the electromagnetic wave which is slowed down by silica matches very closely the dispersion of the electron beam which travels at about half of the speed of light. This ensures high interaction impedance over the whole bandwidth, and consequently, high output power. Fourth, since the modes cannot be confined at frequencies outside of the band gap, the omniguide TWT has a reduced higher-order-mode content. Finally, dielectric structures present one with lower losses at high frequencies than their metallic counterparts, which results in having less of the cooling

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issues for the same output power, and consequently in lighter and more compact devices.

By modifying the dimensions of the omniguide, namely, the diameter and thickness of dielectric tubes, we engineered a structure that resonated at the frequency of interest (95 GHz) and confined a mode at the center with the field pattern resembling the one of the TM_{01}-mode of the cylindrical waveguide (Figure 1(b)). This mode is suitable for effective interaction with the beam. We employed silica which has dielectric permittivity of 3.8 for construction of the omniguide. This material slows the mode to half of the speed of light, which matches the speed of the 120-keV electron beam. This mode is an ideal candidate for the operating mode of a traveling-wave structure. Figure 2 shows the band gap diagram for the silica omniguide structure. The designed structure operates at the lowest band gap, which has a bandwidth over 100 per cent. The dispersion relation for the structure is almost linear and is plotted with dots over the band gap diagram.

The dispersion line for the 120-keV electron beam is also plotted and intersects the dispersion curve of the electromagnetic wave. The omniguide structure is designed to operate near the intersection of the two dispersion curves.

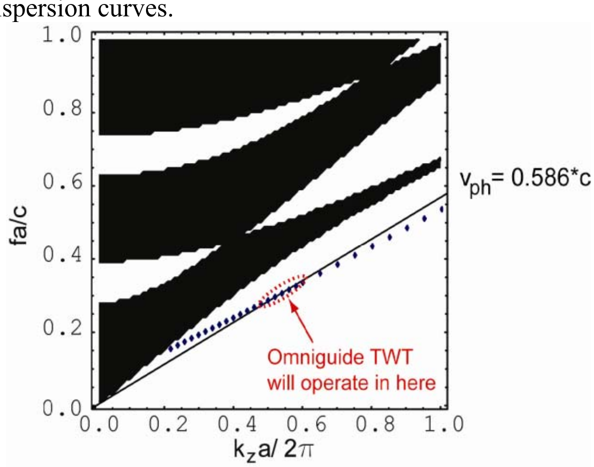

Figure 2: The eigenfrequency of the TM01-like mode of a SiO2 omniguide plotted versus the longitudinal wave vector. The dependence is plotted with dots on top of the band gap diagram: black area corresponds to the range of frequencies where the eigenmode cannot be confined inside an omniguide, white area corresponds to the mode confinement region.

We have conducted end-to-end modeling with the CST Microwave Studio [6] and finalized the design of a W-band silica omniguide TWT. The dimensions of the structure are summarized in Table 1. We have designed a quasioptical coupler for transferring mm-wave power from two WR10 waveguides into the omniguide structure. The CAD drawing of the coupler is shown in Figure 3. Two WR10 waveguides slowly taper into a cylindrical metallic waveguide which is then slowly filled with silica. Metallic waveguide filled with silica opens into the omniguide structure. The power couples through such a system with more than 10 per cent band width.

Table 1: Dimensions of the W-band omniguide TWT structure

Radial period, a	0.92 mm
Thickness of the dielectric layer, d	0.46 mm = 0.5 a
Inner layer ID	0.92 mm = a
Inner layer OD	4.6 mm = 5*a
Structure length	2.54 cm

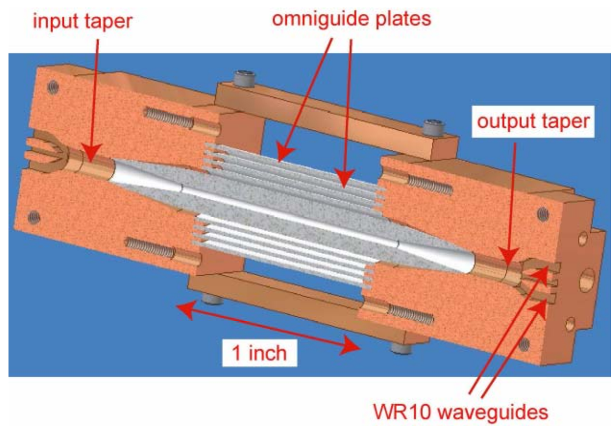

Figure 3: CAD drawing of the omniguide TWT structure and copper couplers.

CONSTRUCTION AND COLD TESTS OF THE OMNIGUIDE TWT STRUCTURES

A cold-test model of the omniguide structure was manufactured. Silica tubes (Figure 4) were manufactured by the Silica Glass Products, Inc. in Willow Grove, PA and fastened in two aluminum end plates. The central tube was tapered slowly to allow for quasi-optical coupling of the microwaves from two WR10 waveguides into the omniguide structure. A symmetrical coupler on the other side of the tube serves for the power output. It should be emphasized that since a PBG structure limits higher order modes, the formidable coupling issue in copper structures (a true limitation to higher power, bandwidth, and frequency scaling) is replaced by this simple coupling design. The structure was tested in our mm-wave laboratory with the HP8510C network analyzer and Oleson Microwave mm-wave heads. The measured transmission curve is shown in Figure 5. The structure transmitted microwaves from 90 to 100 GHz with about 6 dB loss (see the black line in Figure 5), which actually mostly comes from the connection hardware, but not the omniguide structure itself. The large periodic ripples on the transmission curve come from the coupler - the machine shop that cut the silica taper could not fabricate a real taper and actually cut the corners sharp. In Figure 5 the transmission through the LANL vane-loaded TWT structure [3] is shown for comparison with a grey line. It can be easily seen from the figure that the vane-loaded structure has much smaller bandwidth (around 7 per cent) and higher losses (more than 20 dB). Therefore one can

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expect a much better performance from the omniguide structure with respect to mm-wave power generation.

Figure 4: Silica tubes produced by Silica Glass Products, Inc. (photograph).

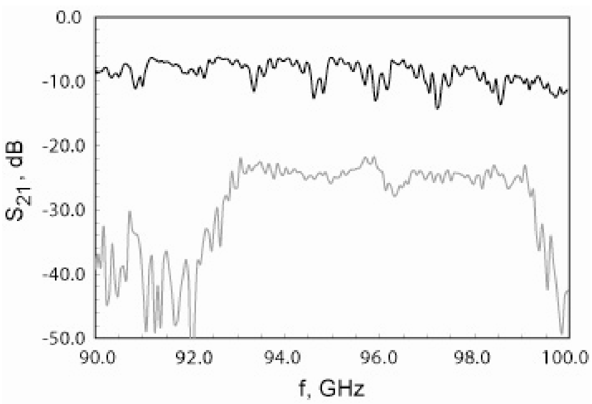

Figure 5: Measured transmission through the omniguide structure (black line). For comparison measured transmission through the LANL W-band vane-loaded TWT structure [3] is shown (grey line).

The structure was next redesigned to fit the solenoid opening in our mm-wave electron beam test stand [3]. The redesigned structure was manufactured with metallic parts made of OFE copper with joints brazed together for high conductivity and good vacuum. The new structure is shown in Figure 6.

CONCLUSION AND PLANS

We have proposed to use the omniguide structures for the construction of a mm-wave traveling wave tube amplifier. Omniguide TWT structures show great promise at mm-waves because of their wide bandwidth, linear dispersion and a potential for cheap manufacturing.

Figure 6: Omniguide TWT structure fabricated for testing with an electron beam (photograph).

An Omniguide TWT structure was manufactured and successfully cold tested at Los Alamos National Laboratory. We have planned a gain experiment with a 2 A, 120 keV electron beam. The structure will be driven from 90 to 100 GHz, and the gain (at low power) will be measured with available diagnostics to verify the interaction concept. Next, we will conduct a moderate power and moderate bandwidth experiment. We plan to demonstrate generation of 100 W of mm-waves with 10 per cent bandwidth. This is well better performance than for the best available commercial mm-wave tubes. We believe that the current design of the structure can be improved even further to achieve the peak output power of the tube of 1 kW and bandwidth of more than 20 per cent.

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