Design and Efficient Coupling of TE_{01} Mode in Small-core THz Bragg Fiber

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***Abstract*—We report a design of small-core, multiple-layer Bragg waveguide for guiding the terahertz (THz) signal using TE_{01} mode, which is composed of alternating high-index dielectric (HDPE) and low-index dielectric (air). The propagation loss is less than 0.1 dB per centimeter ranging from 0.95 THz to 1.20 THz, which is better than that of the traditional metallic tube. Furthermore, a novel scheme is proposed to excite and extract the TE_{01} mode in the Bragg fiber by employing Y-type mode converters. Based on this scheme, for the first time, one can generate the Bragg TE_{01} mode and further apply such wave-guiding system in THz communication or beam-wave interaction for THz generation.**

I. INTRODUCTION

TERAHERTZ (THz) technology has aroused much interest over the past decade, because of many promising applications in communication [1], imaging [2], and biologic science [3]. To improve performance, coherent and high-power THz signal generated by gyrotron has been intensively studied [4]. For the gyrotron to be efficient, a small-core cylindrical metallic waveguide operated near the cutoff of the targeted mode is generally employed for suppressing bunching as well modal competitions. The near cut-off operation, however, suffers from strong ohmic loss (power attenuation > 1 cm^{-1}) [5], which goes against the generation and propagation of THz radiation. A low-loss waveguide with small-core dimension is therefore highly desirable for THz gyrotron.

On a parallel front, hollow-core THz photonic bandgap fibers, such as Bragg fibers, have become an active research topic recently [6-9]. Because of the strong photonic bandgap confinement and their all-dielectric nature, these fibers can exhibit much lower loss compared to their metallic counterpart. To this end, the majority of efforts focused on PBG fibers with large-core dimension which can be used to transport broadband THz radiation for communication [1-3], but are not suitable as interaction tubes for gyrotron due to the extremely serious modal competition.

In this work, we present a design of small-core Bragg fiber with outer metallic cladding operated around one terahertz, which is slightly above the cutoff frequency of the TE_{01} mode for efficient gyrotron operation. The propagation loss of our THz fiber is minimized by using low-loss and high-index-contrast dielectric materials (HDPE and air) as the Bragg layers. Another well-known challenge for operating waveguide with the TE_{01} mode is the difficulty in efficient coupling this mode with the linearly-polarized wave generated by the traditional THz sources. Therefore, we also propose a novel coupling scheme based on a Y-type TE_{01} mode converter to excite the TE_{01} mode in the designed fiber, and quantify its coupling efficiency using rigorous eigenmode expansion method.

II. RESULTS

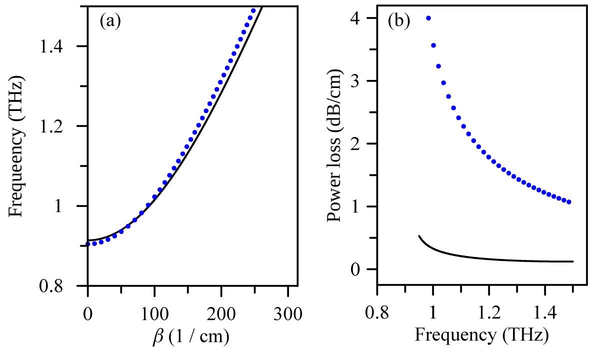

Fig. 1.

Figure 1(a) indicates the dispersion of TE_{01}^{Bragg} mode in the designed Bragg fiber, closely follows that of the metallic waveguide. In particular, the cutoff frequency of TE_{01}^{Bragg} mode is 0.908 THz, very close to that of the TE_{01}^{O} mode in metallic waveguide (0.905 THz). The strong photonic bandgap together with the low material loss of the selected dielectrics renders a low propagation loss less than 0.40 dB/cm over a bandwidth from 0.975 to 1.200 THz as shown in Figure 1(b). This value is nearly one order of magnitude smaller than that of the stainless-steel cylindrical waveguide. This indicates the metal-cladded HDPE/air Bragg fiber is very promising for beam-wave interaction or THz transmission, compared to traditional small-core metallic waveguides

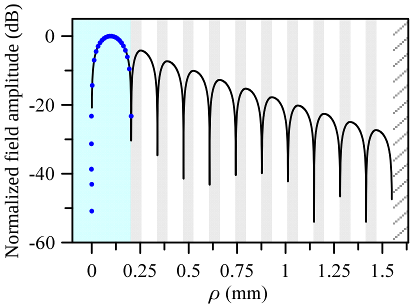

Fig. 2.

Figure 2 compares the radial field distribution at 1.000 THz of the metal-cladded Bragg fiber (solid black curve) and that of the metallic waveguide (blue dots). As indicated, these two waveguides have nearly identical field distributions inside the core. While the electric field in the metallic waveguide reduces to zero at the core's boundary, the field in the Bragg fiber extends into the dielectric layers with oscillating amplitude before it is terminated at the outer metallic wall. This is a characteristic of a Bloch wave with the decaying amplitude in a photonic bandgap. The field amplitude drops to below -20 dB in the last Bragg pair and it effectively reduces ohmic loss at dielectric-metal interface.

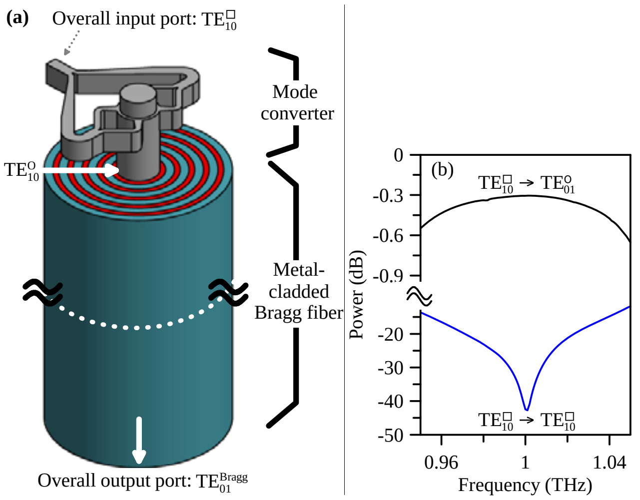

Fig. 3

We also propose a novel scheme to efficiently couple the traditional THz sources with linearly polarized TEM mode to the $\mathrm{TE}_{01}^{\mathrm{Bragg}}$ mode in metal-cladded Bragg fiber by employing a Y-type mode converter [Fig. 3(a)]. The basic idea is to explore the similarity in the field distributions between the metallic cylindrical waveguide and the fiber. Figure 3(b) shows the spectral characteristics of the designed Y-type mode converter, calculated by HFSS using the realistic material property of copper with conductivity of 5.80×10^{7} S/m. Over the major operating band from 0.971 THz to 1.024THz, power transmission coefficient of the TE_{01} mode ($\mathrm{TE}_{10}^{\square} \rightarrow \mathrm{TE}_{01}^{\bigcirc}$) exceeds -0.4 dB [> 90.00%, black curve in Fig. 3(b)] while the power reflection coefficient is less than -20 dB [1.00%, blue curve in Fig. 3(b)]. Specially, the maximum transmission approaches -0.31 dB (93.11%) at 1.0 THz.

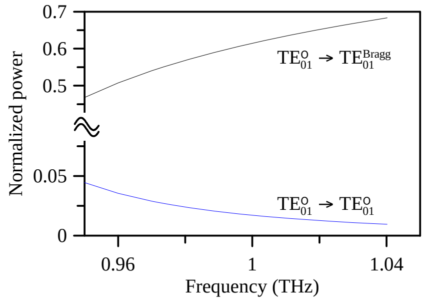

Fig. 4

In the following, the excitation efficiency of the $\mathrm{TE}_{01}^{\mathrm{Bragg}}$ mode in the metal-cladded Bragg fiber by a $\mathrm{TE}_{01}^{\bigcirc}$ mode generated at the end of the mode converter as depicted in Fig. 3(a). Based on the modal analysis (eigenmode expansion analysis), we found that the total reflection power can be less than 0.05 for the whole operating band (blue curve in Fig. 4), indicating that most of the injected power could be coupled into the fiber under the current coupling scheme. On the other hand, the excitation rate of the desired $\mathrm{TE}_{01}^{\mathrm{Bragg}}$ mode is higher than 0.50 (maximum excitation rate can achieve 0.68) (black curve in Fig. 4). To the best of our knowledge, the present coupling scheme is the first demonstration of excitation of TE_{01} mode in a fiber in THz region.

III. CONCLUSIONS

Hollow small-core THz Bragg fiber with metallic cladding, consisting of the alternating HDPE layer and air layer was designed. In order to minimize the conducting loss of the outer metallic cladding as well as the dielectric loss for near-cutoff operation, the layers' thicknesses should be determined by exact quarter-wavelength conditions to guarantee a destructive interference between all of the leaky multiple-reflection waves. The power propagation loss of Bragg TE_{01} mode inside the small-core metal-cladding HDPE/air Bragg fiber is nearly negligible (< 0.4 dB/cm), which is significantly better than the existing stainless steel waveguide in THz region. The features—ultra low propagation loss make our design is more capable of being applied in beam-wave interaction. Finally, a simple scheme for exciting or extracting the TE_{01} mode in a small-core Bragg fiber is presented. With employing additional Y-type mode converter, a relatively high-purity Bragg TE_{01} mode can be coupled. The present scheme is an alternative coupling mechanism and should benefit the other research that require operating at TE_{01} mode.

REFERENCES

[1] J. Federici, and L. Moeller, "Review of terahertz and subterahertz wireless communications," J. Appl. Phys. **107**, 111101 (2010).

[2] J. F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, and D. Zimdars, "THz imaging and sensing for security applications - explosives, weapons and drugs," Semicond. Sci. Tech. **20**, S266-S280 (2005).

[3] P. H. Siegel, "Terahertz technology in biology and medicine," IEEE Trans. on Microwave Theory and Tech. **52**, 2438-2447 (2004).

[4] K. R. Chu, "The electron cyclotron maser," Rev. Mod. Phys. **76**, 489-540 (2004).

[5] G. Gallot, S. P. Jamison, R. W. McGowan, and D. Grischkowsky, "Terahertz waveguides," J. Opt. Soc. Am. B **17**, 851-863 (2000).

[6] M. Skorobogatiy, and A. Dupuis, "Ferroelectric all-polymer hollow Bragg fibers for terahertz guidance, " Appl. Phys. Lett. **90**, 113514 (2007).

[7] A. Dupuis, K. Stoeffler, B. Ung, C. Dubois, and M. Skorobogatiy, "Transmission measurements of hollow-core THz Bragg fibers," J. Opt. Soc. Am. B **28**, 896-907 (2011).

[8] B. Ung, A. Dupuis, K. Stoeffler, C. Dubois, and M. Skorobogatiy, "High-refractive-index composite materials for terahertz waveguides: trade-off between index contrast and absorption loss," J. Opt. Soc. Am. B **28**, 917-921 (2011).

[9] S. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. Engeness, M. Soljacic, S. Jacobs, J. Joannopoulos, and Y. Fink, "Low-loss asymptotically single-mode propagation in large-core OmniGuide fibers," Opt. Express **9**, 748-779 (2001).