THz Waveguides, Devices and Hybrid Polymer-chalcogenide Photonic Crystal Fibers

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Abstract— In this contribution, we review our recent activities in the design, fabrication and characterization of polymer THz waveguides. Besides the THz waveguides, we finally will also briefly show some of our initial results on a novel hybrid polymer photonic crystal fiber with integrated chalcogenide glass layers.

1. INTRODUCTION

Waveguides and functional devices in the Terahertz range have attracted considerable interest in recent years because they can offer the opportunity to develop compact, reliable and flexible THz systems

In this paper, we will first present a novel polymer (TOPAS) solid-core Photonic Crystal Fiber (PCF) with ultra-wide bandwidth, which is bendable and has low loss and unique dispersion properties. Then we demonstrate both numerically and experimentally a novel band-gap THz fiber design, which consists of a honeycomb cladding structure with a porous core. This structure uses Photonic Bandgap (PBG) guidance, while keeping the loss at low levels due to its special porous-core. Last but not least, we will also demonstrate a special design of a broadband THz directional coupler, which uses mechanical down-doping of the two cores. We show how this provides a broad bandwidth with relative low device loss and we performe a detailed optimization of the coupler design to maximize bandwidth and minimize loss.

Besides THz waveguides and devices, we also demonstrate a novel way to develop hybrid polymer photonic crystal fiber with integrated chalcogenide glass layers based on a solution-processed method. The proposed integration method allows the deposition of nanofilms with a wide range of nonlinear glasses and potentially offers the possibility for multi-layer deposition of different glasses inside the holes of the polymer PCF.

2. SOLID-CORE PCFS

We fabricated THz fibers based on the structure of solid-core PCFs [1], which guides by total internal reflection. The fibers were fabricated by using drill-and-draw technology and made of the cyclic olefin co-polymer TOPAS. The reason for using TOPAS is because it has very low loss and flat dispersion in the THz range. The images of the fabricated fibers with two different hole diameter (d) to pitch (Λ) ratios are shown in Figs. 1(a) and 1(b).

The fiber loss, measured using the cutback method, is shown in Fig. 1(c). The results show that the fiber can have propagation losses lower than the bulk material loss of TOPAS (gray line in Fig. 1(c)).

The spectrograms in Figs. 1(d) and (e) show a short time FFT of the THz pulse after propagation through a 26 mm Small-Mode Area (SMA) fiber and through a 29 mm Large-mode area (LMA) fiber, respectively. Overlaid on the spectrograms are the time traces of the electric field of the THz pulses. The results show the strong dispersion of the SMA fiber and small dispersion of the LMA fiber, which agree well with the calculated dispersion profiles shown in Figs. 1(f) and 1(g). Due to the strong confinement of the field in the solid core the fibers can be bent without significant increase in loss [1], which indicates that the proposed fibers are tolerant towards sharp bends of the fiber.

3. POROUS-CORE PBG TYPE FIBERS

Although some polymer materials such as TOPAS [1] and Zeonex [2], have relative low loss in the THz region compared to other polymer materials such as PMMA, their loss levels are still high.

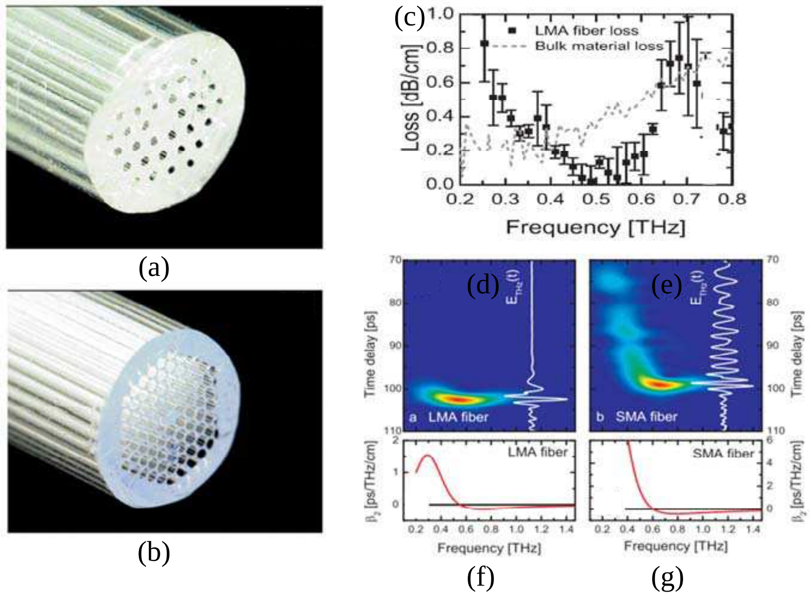

Figure 1: (a) Image of the LMA and (b) SMA fibers, respectively. (c) Frequency dependant loss of the LMA fiber. Spectrogram and temporal profile of the THz pulse after propagation through (d) 26 mm SMA fiber and (e) 29 mm LMA fiber. Calculated dispersion for (f) SMA and (g) LMA fiber.

Dry air is transparent in the THz region and thus an effective approach to lower the propagation loss of a THz waveguide is to maximize the fraction of the power propagating in air, while still being confined to a waveguide. Towards this point, hollow-core PBG fibers are good candidates due to the fact that they can confine most power in the air-core as well as have flexibility in the design of critical parameters such as center frequency, bandwidth, and dispersion. However, good-quality hollow-core PBG THz fibers have so far been difficult to draw, mainly due to the different expansion ratios of holes with different diameter during the drawing process.

To overcome the fabrication problems of differently sized holes in the hollow core THz fiber, a novel porous-core honeycomb bandgap design was numerically and experimentally investigated [3, 4]. Basically it consists of a hollow-core PBG THz fiber cladding structure (honeycomb) with a porous core (the same size as cladding hole) inserted into the hollow core. This allows PBG guidance, while still keeping the loss low due to the porous core. Due to the increased effective index of the core, the cladding PBG structure is a honeycomb structure, which from optical fibers is known to more easily allow broad bandgaps.

The fact that all air-holes are of the same size results in a fiber that can be drawn with much higher precision and reproducibility than a corresponding air-core fiber. Figs. 2(a) and 2(b) show an idealized structure and a microscope image of the end facet of the proposed porous-core honeycomb

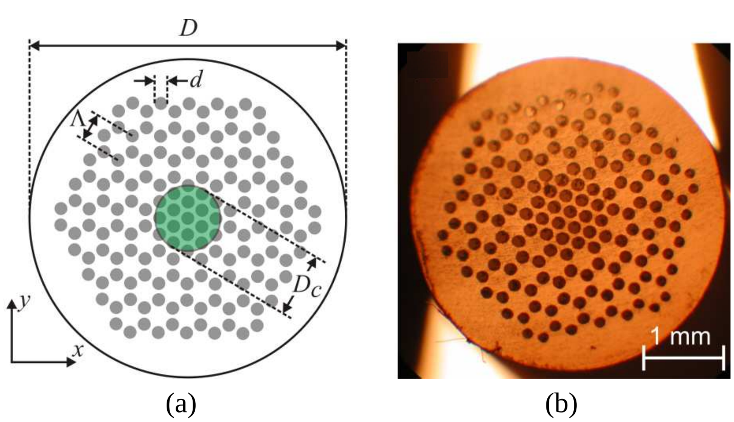

Figure 2: (a) Idealized structure used in the simulation ($d = 165\,\mu\text{m}$, $\Lambda = 360\,\mu\text{m}$). (b) Microscope image of the actual fiber.

bandgap THz fiber, respectively. The high-precision hole structure provides very clear bandgap guidance and the location of the two measured bandgaps agree well with simulations based on finite-element modeling (not shown here). Moreover, it was shown in Figs. 3(a)–(d) that cladding mode can be effectively stripped away by adding an absorptive water layer around the fiber. Fiber loss measurement results shown in Figs. 3(e)–(g) reveal the frequency-dependent coupling loss and propagation loss, and the fact that the fiber propagation loss can be significantly lower than the bulk material loss (dash line in Fig. 3(g)) within the first band gap between 0.75 and 1.05 THz.

4. 3-dB THz FIBER DIRECTIONAL COUPLERS

Due to the progress in THz fibers and waveguides, it has now become possible to develop THz devices. THz directional couplers are particularly interesting due to their controllable directional power transfer between fiber cores. However, most of the reported THz couplers have in common that they only have a constant coupling length over a narrow bandwidth. For removing the bandwidth limitation, very recently, one kind of broadband THz directional fiber coupler working in the THz region was proposed [5, 6]. Broad transmission was achieved by using down-doping in two cores of a dual-core PCF. Instead of normal chemical down-doping a mechanical down-doping was implemented by using a triangular array of air holes, which can be easily achieved by drill-and-draw technology [1]. The cross section of the proposed coupler, together with an enlarged view of the doped core is shown in Fig. 4(a). The downdoped cores experience mode-field diameter minima

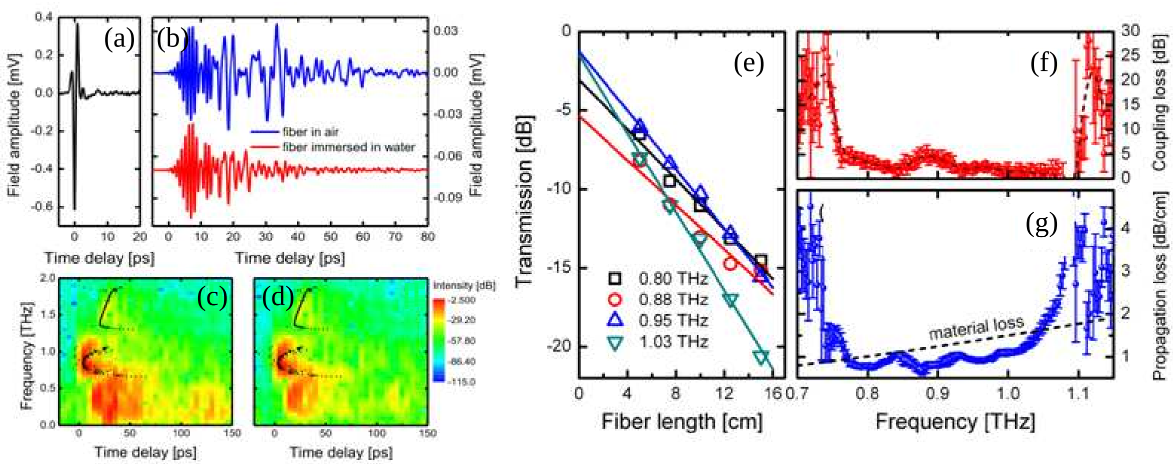

Figure 3: Measured THz pulse for (a) reference signal and (b) transmitted pulse through a 5 cm long honeycomb fiber with water (red curve) and air (blue curve) around the surface. Short-time Fourier transforms of the transmitted waveforms in (b) are shown in (c) and (d), respectively, with simulated group velocity arrival times of the spectral components overlaid. (e) Relative transmission of the fiber with different lengths. (f) Coupling loss (red symbols), (g) Frequency dependent propagation loss of the fiber (blue data markers) and material loss of TOPAS (dashed line).

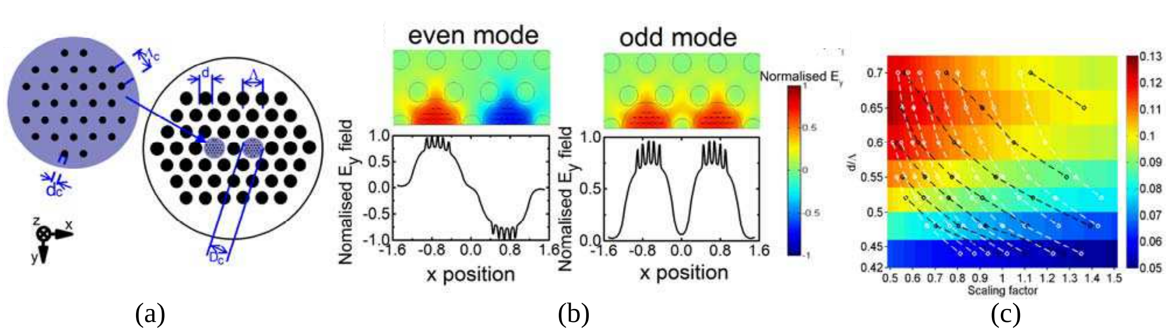

Figure 4: (a) Cross section of the air-doped dual-core coupler. (b) Electric field profiles at 0.9 THz (y polarization) of even and odd super-modes. (c) Optimum FOM ($\Lambda = 682.5$ µm and $\Lambda_c = 102.375$ µm at $m = 1$) versus d/Λ and scaling factor m. Black dashed lines have fixed center frequency from 0.6 to 1.4 THz with a step of 0.1 THz. White dashed lines have fixed 3-dB bandwidth from 0.15 to 0.4 THz with a step of 0.05 THz (right to left).

(corresponding to maximum coupling length), at which the first derivative of the coupling length vanished, which results in a bandwidth broadening.

Due to the existence of a huge parameter space (d, Λ, d_c, Λ_c), further work was done by a thorough numerical design optimization of the structure parameters. Optimizations were performed by using a figure of merit (FOM), which takes both the 3-dB bandwidth and device loss into account [5, 6]. Fig. 4(c) shows the optimum FOM of the coupler for different d/Λ as a function of a scaling factor, which scales, or multiplies, all geometrical parameters of the coupler. Note here that the optimum FOM without scaling is obtained by fixing $\Lambda = 682.5\,\mu$m. Simulation results show that at a center frequency of 1 THz a structure with suitable parameters can have a large bandwidth of 0.25 THz and relative low device loss of 9.2 dB [6]. In the work, single-mode guidance within the desired working region was also verified for the optimum coupler (not shown here).

5. HYBRID POLYMER-CHALCOGENIDE PCFS

A novel hybrid polymer PCF with integrated chalcogenide glass layers was fabricated using a solution-based method [7]. Fig. 5(a) shows a SEM image of the initial fabricated PMMA PCF and Fig. 5(b) shows the SEM image after the deposition of the chalcogenide films inside the cladding holes of the fiber (using a concentration of ~400 mg As_2S_3 in 1 mL of n-butylamine). After the solvent evaporation, energy dispersive X-ray (EDX) analysis was used to verify the existence of As (arsenic) and S (sulfide) lines as can be seen from Fig. 5(c). Fig. 5(d) shows the normalized transmission (black line) of a 4-cm long hybrid fiber and how the transmission edge shifts after the increase of the power (red line). This is because the ultra-high Kerr nonlinearity of the chalcogenide glass makes the polymer PCF nonlinear and consequently red-shifts the long wavelength band edge as the power increases. The proposed fabrication technique constitutes a new highway towards all-fiber nonlinear tunable devices based on polymer PCFs.

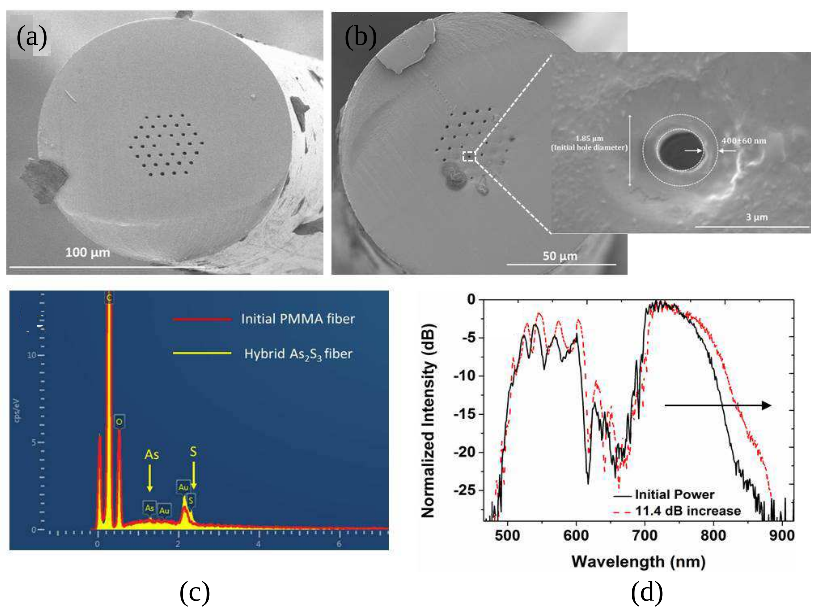

Figure 5: SEM image of the (a) fabricated PMMA PCF and (b) the hybrid chalcogenide/PMMA PCF. Inset is magnified single hole showing the thickness of the chalcogenide film to be ~400 nm. (c) Energy dispersive X-ray spectroscopy verifying the existence of the Arsenic and Sulfide elements on the inner wall of the air-holes. (d) Normalized transmission spectrum of the hybrid fiber at two different power levels.

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