Resonant THz sensor for paper quality monitoring using THz fiber Bragg gratings

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We report fabrication of THz fiber Bragg gratings (TFBG) using CO2 laser inscription on subwavelength step-index plastic fibers. A fiber Bragg grating with 48 periods features a ∼4 GHz-wide stop band and about 15 dB transmission loss in the middle of a stop band. The potential of such gratings in the design of resonant sensors for the monitoring of paper quality is demonstrated. Experimental spectral sensitivity of the TFBG-based paper thickness sensor was found to be ∼0.67 GHz/10 μm. A 3D electromagnetic model of a Bragg grating was used to explain experimental findings. © 2013 Optical Society of America

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Terahertz (THz) waves offer unique opportunities that are not available at other wavelengths. First, THz radiation is nonionizing, which can be employed for safe imaging. Second, many materials, such as ceramic [1], plastic [2], and paper-based materials [3], are relatively transparent for THz radiation. Hence, innovative security and quality control applications are envisioned by utilizing THz waves. Most of the current THz sensors are realized in the nonresonant configurations where the sample is interrogated directly by the THz light. In resonant sensors, changes in the sample properties are measured indirectly by studying variations in the optical properties of a resonant structure coupled to a sample. In this Letter, we study the use of THz fiber Bragg gratings (TFBGs) for resonant THz sensing.

Fabrication of the TFBGs requires the availability of the low-loss waveguides. One of the simplest examples of a low-loss THz waveguide is a subwavelength step-index plastic fiber [4]. In such fibers a large fraction of the modal power is found outside of the fiber core, which not only significantly reduces the transmission losses but also makes such fibers a promising platform for sensing applications. Recently, fabrication of several fiber-based components, such as TFBGs [5] and THz notch filters [6], was reported using laser inscription on THz fibers. A very precise, but expensive, excimer laser system was used for inscription.

In this work we demonstrate fabrication of TFBGs using a cost effective CO2 laser inscription system, which is widely used for long period grating fabrication on silica fibers in the near-IR [7,8]. Optical response of such gratings and their application in sensing were studied theoretically using the Grating MOD module from RSoft Design Group. Fabricated TFBGs were then used to build prototypes of resonant multimeasurand sensors for monitoring paper quality, which is an important manufacturing problem [3]. Due to the lack of space, in this letter we only present the use of such sensors for paper thickness monitoring, while only indicating the other sensing modalities.

The subwavelength step-index fibers with a diameter of 400 μm were drawn in-house from the low density poly styrene (LDPE) rods. LDPE has a relatively low material loss (∼0.2 cm−1) and an almost constant refractive index (RI) of 1.54 in the 0.2−0.5 THz region studied in this work [4]. TFBGs were then inscribed point by point on the 5 cm long pieces of step-index LDPE fibers, using a class IV Synrad CO2 laser operating at 10.6 μm, with average output power of 1.5 W and repetition rate of 20 kHz. The TFBG presented in this report consists of 48 notches that are ∼110 μm deep and ∼170 μm wide [see Fig. 1(a)]. The grating period is designed to be 340 μm, in order to place the TFBG stop band in the low-loss transmission window of the subwavelength fiber, which is centered at ∼0.3 THz. The TFBG total length is 17 mm.

The TFBG transmission spectra were recorded using a THz time domain spectroscopy (TDS) setup modified for fiber measurements [10]. In our studies, we used ~600 ps long scans that resulted in a spectral resolution of ~1.5 GHz. A ∼4 GHz wide stop band (full-width at

Fig. 1. Microscope images of (a) the fabricated TFBG and (c) the paper thickness monitoring setup. Schematics of (b) the TFBG 3D geometry and (d) the sensor setup.
half-maximum) at ∼375 GHz and ∼15 dB transmission loss in the middle of a stop band were observed (see Fig. 2). Similar to the fiber Bragg gratings in the near-IR, spectral position and shape of the TFBG transmission peak are sensitive to changes in the environment, which opens an opportunity for their use in sensing and monitoring.

In our simulations, TFBG transmission spectra were modeled using the Grating MOD (RSoft Design Group) software module, which is based on the Coupled-Mode Theory and the transfer matrix method [11]. The geometrical model of the TFBG is simply a solid cylinder with multiple annular indentations that represent notches [see Fig. 1(b)]. The cross section of the notches is shown in Fig. 1(b), which is an intersection of the two rods (black dash curves) with diameters of 400 μm and center-to-center distance defined as depth of the notch. An enlarged 3D geometrical model of one period is also given in Fig. 1(d). The geometrical parameters, such as width and depth of the notches, were measured from the Bragg grating micrographs like the one presented in Fig. 1(a). Forty-eight grating periods were simulated with a period of 340 μm, notch depth of 110 μm and notch width of 170 μm. The transmission spectrum of the TFBG without the paper layer is shown in Fig. 2. When compared to the experimental results, the transmission loss and the dip position of the experimental results fit very well with the simulated ones. The width of the TFBG peak is somewhat larger (∼7 GHz) than the experimental one, which is largely due to geometrical differences between simulated and experimental notch profiles.

Next, we measured the frequency dependent refractive index and absorption coefficient of the Origami paper by using the same THz TDS setup. Similar to the cut-back method, transmission measurements through the stacks of 2, 4, 6, and 8 layers of 60 μm thick Origami paper were carried out and the paper absorption loss and refractive index were extracted from this data. The results are shown in Fig. 3. The refractive index of the Origami paper (blue circles) is relatively constant, ∼1.43 in the 0.2–0.4 THz frequency range, which is consistent with the measurements in [9]. The paper absorption coefficient (red squares in Fig. 3), however, shows rapid increase at higher frequencies from ∼5 cm⁻¹ at 0.2 THz to ∼20 cm⁻¹ at 0.6 THz. In the frequency range of a TFBG stop band 0.3–0.4 THz, the absorption coefficient is ∼4 cm⁻¹.

We now study changes in the TFBG transmission spectrum in response to changes in the thickness of a paper stack, which is brought in contact with the grating [see Fig. 1(d)]. In our simulations we use experimentally measured values of the paper refractive index, absorption coefficient, and paper thickness to obtain the TFBG transmission curves presented in Fig. 4. We note that the TFBG transmission dip shifts toward lower frequencies, from 373.8 to 356.3 GHz, (longer wavelengths) as the paper stack thickness increases from 60 to 240 μm. This behavior is a simple manifestation of an increase in the TFBG modal effective refractive index n_eff due to presence of paper in the grating vicinity. As higher modal refractive index results in longer Bragg wavelength, a λ_B = 2n_effΛ, hence, the grating peak shifts to lower frequencies for thicker paper stacks.

From the results in Fig. 4, we can estimate the spectral sensitivity of our sensor to changes in the paper thickness as ∼0.73 GHz/10 μm. Given that the spectral resolution of our THz TDS setup is 1.5 GHz, the minimal measurable change in the paper thickness is expected to be ∼20 μm.

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**Fig. 2.** Comparison between simulated and experimental transmission spectra of TFBG.

**Fig. 3.** Frequency dependence of the refractive index (blue circles) and absorption coefficients (red squares) of the Origami paper.

**Fig. 4.** Simulated TFBG transmission spectra for a different number of paper layers placed in direct contact with TFBG.
Furthermore, it is clear from Fig. 4 that, outside of the TFBG stop band, the use of thicker paper stacks results in higher transmission loss. This finding is simple to rationalize as, in the presence of thicker stacks, the guided grating mode will have a stronger presence in the lossy paper region. This can be used as a supplementary method for monitoring paper thickness and humidity content. Thus, from Fig. 4, we deduce that at 0.375 THz the amplitude sensitivity to changes in the paper thickness is ~0.8 dB/10 μm, which is quite high. In practice, however, we find that amplitude measurement with our THz setup is considerably more sensitive to noise than a spectral measurement, thus making amplitude detection a considerably less sensitive and less attractive alternative.

To test our numerical predictions, experimental measurements of the TFBG transmission spectra have been performed for various numbers of paper layers placed in direct contact with a TFBG [see Figs. 1(c) and 1(d)]. The paper sheets were of the same width as the grating region (17 mm). By placing more layers of the Origami paper in contact with a TFBG, the position of the transmission dip shifted proportionally to the paper thickness, from 373.4 to 357.3 GHz [see Fig. 5(a)]. Comparisons between simulation and experimental results show very good correspondence in the center peak position [see Fig. 5(b)]. Experimental spectral sensitivity of the peak position changes in the paper thickness is found to be ~0.67 GHz/10 μm, which agrees very well with the simulated one, ~0.73 GHz/10 μm. By comparing Fig. 5(a) with Fig. 4 we note that the measured transmission losses are somewhat smaller than the simulated ones. We attribute the lower measured losses to the fact that paper layers in the stack are not tightly pressed, thus allowing some low-loss air regions between the paper layers. Using the measured sensitivity value we conclude that, with a current THz setup that offers 1.5 GHz resolution, we can reliably detect ~20 μm variations in the paper thickness. Such sensitivities are high enough to be of interest for real-time monitoring of paper manufacturing lines.

Finally, we note that instead of using spectrally interrogated TFBGs, as we did in this paper, an alternative method of paper thickness monitoring is via detection of changes in the modal refractive index of a subwavelength fiber (without grating) suspended over the paper, which constitutes the phase interrogation modality. Phase interrogation can also be implemented in our setup by analyzing phase changes in the TFBG transmitted signal at frequencies outside of the stop band. A more detailed analysis shows that spectral-based and phase-based interrogation methods are both low noise and their sensitivities are quite comparable. In TFBGs, both interrogation modalities can be exploited simultaneously using the same THz scan in order to generate two complimentary data streams for reliable detection of changes in the paper thickness.

Ultimately, we believe that TFBG represents a convenient technological platform for combining all three interrogation modalities (spectral, amplitude, and phase) in the same sensor in order to realize a reliable multimeasurand sensor system with redundant data streams.

References