Measurement of chromatic dispersion and Raman gain efficiency of a hole-assisted fiber: Influence of bend

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Abstract: We have experimentally measured the Raman gain efficiency (RGE) and chromatic dispersion (CD) of a hole-assisted fiber (HAF). The RGE of a HAF was characterized using standard pump on/off technique while the CD of the fiber was measured using optical network analyzer. Theoretical simulations of modal characteristics and RGE of a HAF were carried out using an accurate full-vectorial finite element method. Further, the bending effects on the CD and the RGE of a HAF with a smallest feasible bending radius are demonstrated. It was found that the CD increases while the RGE is decreased if the HAF is bent in a smallest bending radius of 5 mm. Numerical predictions from the theory are shown to be in good agreement with the experimental results.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2300) fiber measurements

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1. Introduction

Photonic crystal fibers (PCFs) or microstructured optical fibers (MOFs) or holey fibers (HFs) have been the subject of intensive research since their first demonstration in 1997 [1]. Another kind of PCF variant, where the core is doped with germanium and cladding has either one or two rings of air-holes, is widely known as hole-assisted fiber (HAF) and can be used in optical wiring and local area networks with sharp bends [2]. To compensate for high optical losses in HAFs, it becomes important to know their amplification properties. The Raman amplification properties of PCFs have been studied extensively along with dispersion compensation which suggests them to be a next frontier of fiber amplifiers as they offer better amplification characteristics than the conventional ones [3-11]. Matos *et al*. [5] measured the Raman gain efficiency (RGE) of a HF using a high pump power based on pump on/off technique. However, no efforts have been made so far to measure the RGE and chromatic dispersion (CD) of HAF. To deploy HAFs in local area networks, it is an immediate demand of the industry or market to know their characteristics accurately.

In this paper, for the first time, we have experimentally characterized the RGE and the CD of a HAF [2], where the HAF has eighteen air-holes in the cladding with a germanium doped core region. The HAF was placed in a standard fiber Raman amplifier configuration with a counter-propagating pump. To support our experimental results, we have simulated HAF model using a full-vectorial finite element method (V-FEM) [12] and compared the results. From theory, the peak RGE, corresponding to a frequency shift of 13.2 THz, is calculated as 0.62 $W^{-1}.km^{-1}$ for a 1450 nm depolarized backward propagating pump. By measuring the Raman gain with pump on/off technique, we found a 0.536 $W^{-1}.km^{-1}$ peak RGE value, which is in good agreement to the theoretically evaluated RGE, whereas the numerically evaluated CD was 21.16 ps/nm/km at 1550 nm and the measured dispersion was 21.56 ps/nm/km at 1550 nm. Further, we have also measured the RGE of a standard single mode fiber (SMF) fabricated by Sumitomo Elect. Co. Ltd, whose geometrical characteristics can be found in Ref. [13]. The peak RGE of SMF was obtained as 0.37 $W^{-1}.km^{-1}$ at a frequency shift of 13.2 THz for a depolarized pump of 1450.7 nm, which matches 100 % to the reported value in Ref. [14]. And hence this validates our experimental procedure as well as set-up to characterize the RGE of HAFs. In addition, we have also examined the influence of the bending on amplification as well as CD of the HAF as it has been proposed [2] that HAF can be used in metropolitan network wiring with sharp corners. Therefore, it becomes important to know the influence of the bend on both RGE and CD of the HAF. We have demonstrated the influence of the smallest feasible bending radius of 5 mm on the RGE and CD of the HAF. It was observed that the RGE decreases whereas the CD increases when HAF is bent into a 5 mm bending radius. Moreover, we have also measured the background loss of the HAF using an ASE and white light source. In a summary, we can conclude that numerical predictions from the theory are shown to be in good agreement with the experimental results.

2. Theory and experimental set-up

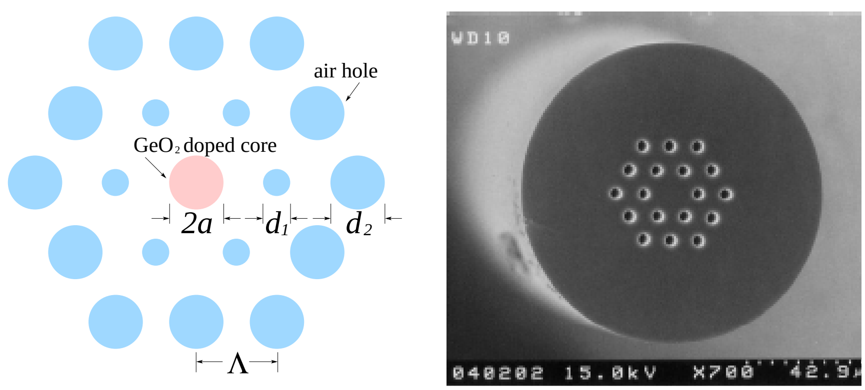
Figures 1(a) and (b) show the transverse cross-section and SEM image of a HAF with shown geometrical parameters, where a is the radius of the doped region, d_1 and d_2 are the hole-diameters of first and second air-hole rings, and Λ is the separation between two air-holes. The geometrical parameters of HAF as shown in Fig. 1(a) are given in Ref. [2]. The HAF is 1025 m long and exhibits an attenuation of 2.3 dB/km at 1550 nm. Figure 2 shows the experimental set-up where a tunable laser source (TLS) with sweeping range from 1520 to 1620 nm was connected to the fiber under test (FUT) through an optical isolator to restrict the back reflection as well as to stop the residual pump entering into the source. The Raman pump was set to propagate into backward direction in order to cancel out the polarization effects and amplitude fluctuations from pump to signals. The pump power was fed into the fiber through a three-port optical circulator while the amplified signals were recorded by an optical spectrum analyzer (OSA). An isolator was used before OSA to stop the reflections entering into the device. Through this experimental set-up, we have characterized the RGE defined as the Raman gain coefficient normalized by effective mode area instead of Raman gain coefficient as it is more useful and practical to quantify the RGE, γ_R, for a fiber Raman amplifier and is expressed in units of [$W^{-1}.km^{-1}$]. The RGE obtained by measuring the on/off Raman gain is given as [15],

$$\gamma_R = \frac{G}{4.343 \times L_{eff} \times P_p} \tag{1}$$

where, G [dB] is the on/off Raman gain, P_p [W] is the input pump power, and L_{eff} [km] is the effective length and is expressed as,

$$L_{eff} = \frac{1 - \exp(-\alpha_p L)}{\alpha_p} \tag{2}$$

where, α_p is the fiber attenuation at pump wavelength and L is the length of FUT. For a specific fiber whose characteristics such as length and attenuation coefficient at pump are known, the RGE can be obtained after measuring the on/off Raman gain through Eqs. (1) and (2).



(a) (b)

Fig.1. (a) Transverse cross-section and (b) SEM image of the fabricated HAF.

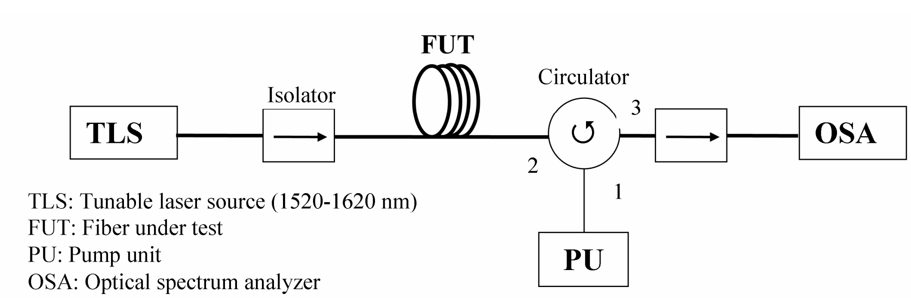
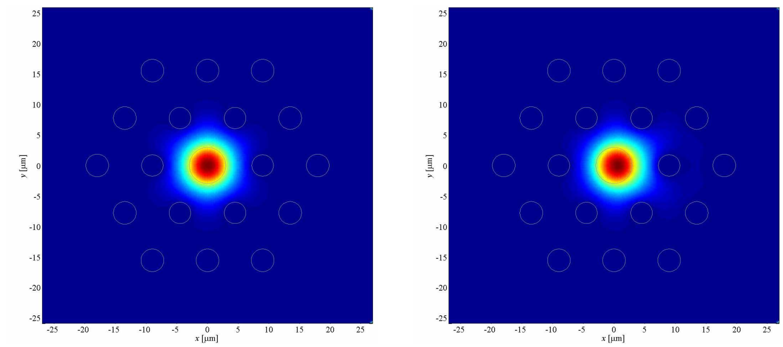


Fig. 2. Experimental setup for measuring on/off Raman gain.

Through V-FEM, we have simulated the HAF with and without bending. Figures 3(a) and (b) illustrate the modal field distributions corresponding to 1550 nm wavelength in a straight HAF and with a smallest bending radius of 5 mm. The straight case is equivalent to a fiber spooled in a bending radius of 5-6 cm where the bending loss doesn't affect its performances. It can be clearly visualized from the electric field distribution of a fundamental mode that the modal field (*x*-component of the electric field) is shifted to right when the HAF is bent into a smallest bending radius of 5 mm and influences its amplification and dispersion characteristics as demonstrated further.



(a) (b)

Fig. 3. The modal field distribution (E_x-component) of a fundamental mode at 1550 nm for a HAF (a) without bending and (b) with a 5 mm bending radius.

3. Experimental results

As discussed in section 2, the pump is launched into counter-propagation direction. Two pump laser diodes are combined with a degree of depolarization of 10% and the drive current was set to 700 mA and tunable laser source was set to emit the signals in C-band (1530-1570 nm) with a step wavelength of 2 nm. We have measured the peak pump power, the peak wavelength, and the pump bandwidth of the input pump. The recorded pump spectrum is depicted in Fig. 4 (a), where we can see that the pump unit emits a single wavelength peaked at 1450.7 nm with a power of 22.4 dBm (173.8 mW) and bandwidth of 2.3 nm. Next, we confirm and validate our experimental set-up and procedure by measuring the RGE of a 25 km standard SMF which was provided by Sumitomo Elect. Co. Ltd. [13]. The measured on/off Raman gain for SMF is depicted in Fig. 4(b) and it can be examined that SMF shows a net peak Raman gain of 3.62 dB at 1550.6 nm. Using Eqs. (1) and (2), the RGE for SMF is computed as 0.37 $W^{-1}.km^{-1}$ and the corresponding frequency shift is 13.3 THz for a depolarized pump of 1450.7 nm, which agrees very well with the reported values in Ref. [14]. The attenuation spectrum of an optical fiber is equally an important characteristic that determine the amplification as well as the information capacity of an optical fiber. Therefore, in the view of deployment of HAF in local area networks, we measure it loss spectrum as shown in Fig. 4(c) which is an important parameter to rate its Raman amplification characteristics.

It is revealed from the attenuation measurements (shown in Fig. 4(c)) that the HAF shows attenuation values of 2.59 dB/km (using ASE light source) and 2.63 dB/km (using white light source) at 1550 nm which are in good agreement with the reported value of 2.3 dB/km at 1550 from Mitsubishi Cable Ind. that used a cut-back technique for a non-spliced HAF. However, in our measurement case, the HAF was spliced with conventional SMF with a total splice loss of 0.16 dB.

Further, we have measured the on/off Raman net gain and the CD of HAF with and without bend. The measured Raman net gain includes the connector-connector loss and the splice between conventional SMF and HAF. After recording the on/off gain, the RGE of a HAF is computed according to the Eqs. (1) and (2). The spectral variation of RGE is exhibited

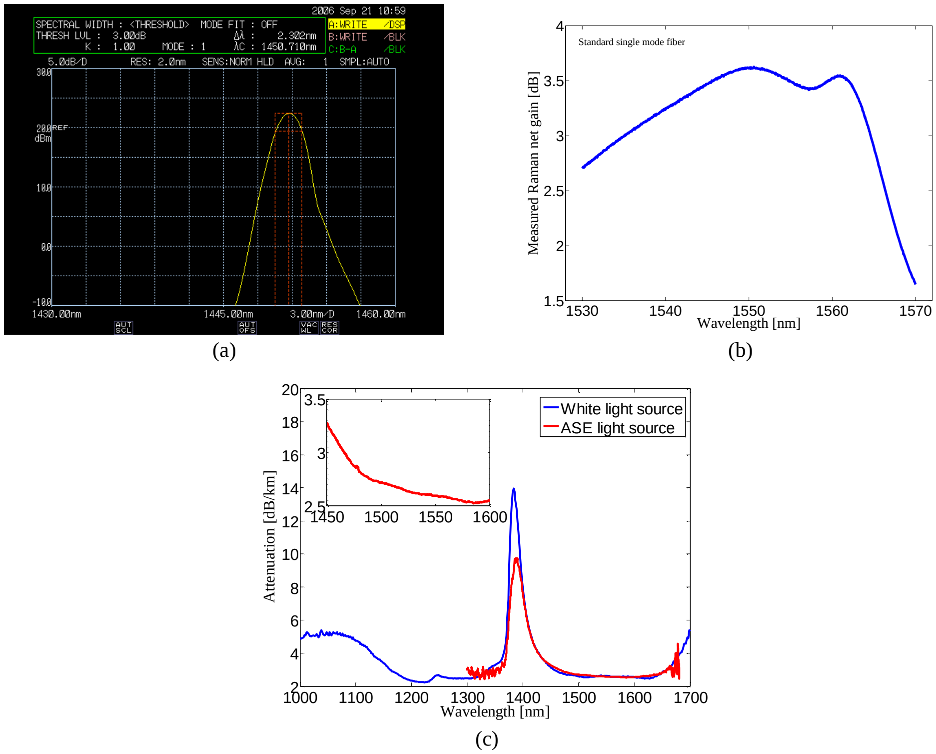


Fig. 4. (a) Trace of an input pump with peak power and wavelength of 22.4 dBm and 1450.7 nm, (b) recorded Raman net gain for a standard SMF from Sumitomo, and (c) the measured attenuation spectrum for a HAF using white (solid blue curve) and ASE (solid red curve) light source.

in Fig. 5. The solid blue curve corresponds to the numerically evaluated RGE when HAF is straight and splice loss was not taken into account. It can be deduced from the results that the peak RGE at a frequency shift of 13.2 THz is 0.618 W^{-1}. km^{-1} for a depolarized pump of 1450 nm. The solid red curve in the same graph presents the RGE when the HAF is bent to a 5 mm bending radius. It is noticed that the RGE decreases when the fiber is bent into a bending radius of 5 mm that is attributed due to the reduction of the overlap between pump and signal as the modal field is shifted from the core to the right as demonstrated in the electric field distribution of the fundamental mode in Fig. 3(b). The peak RGE of a bent HAF is computed as 0.563 W^{-1}. km^{-1}. The solid black curve in Fig. 5 corresponds to the experimentally measured RGE of a HAF which was spooled in a bending radius of 5-6 cm and that resembles to a straight fiber. The peak RGE obtained after measuring the on/off gain for HAF is 0.536 W^{-1}. km^{-1} for a depolarized pump of 1450.7 nm, which is 8% lesser than the peak RGE evaluated theoretically. We believe that this discrepancy between the theoretical and experimental results is acceptable and arises due to the fact that in numerical calculation of the RGE, the insertion loss due to optical components used in experiments and splice loss between SMF and HAF were ignored. The theoretical calculation of RGE of an optical fiber is described in appendix A.

Finally, we have measured the CD of a HAF using an optical network analyzer (Advantest Q7761) that comprises an optical test unit and light source. The results are shown in Fig. 6. The solid blue curve corresponds to numerically evaluated CD of a straight HAF, whereas the solid red curve stands for the CD when the HAF is bent into a smallest bending radius of 5 mm. It is clear from the graph that the CD of HAF increases when the fiber is bent into a 5 mm bending radius. The black dots represent the experimentally measured CD of HAF that was spooled in bending radius of 5-6 cm and can be considered to a straight fiber case. The CD and peak RGE of HAF at 1550 nm with and without bending from theory and experiment are summarized in Table 1. The HAF shows the numerically evaluated CD of 21.16 ps/nm/km and experimentally measured CD of 21.56 ps/nm/km at 1550 nm wavelength. It can be fairly seen from Table 1 that the results from the theory are in good agreement with the experimental results.

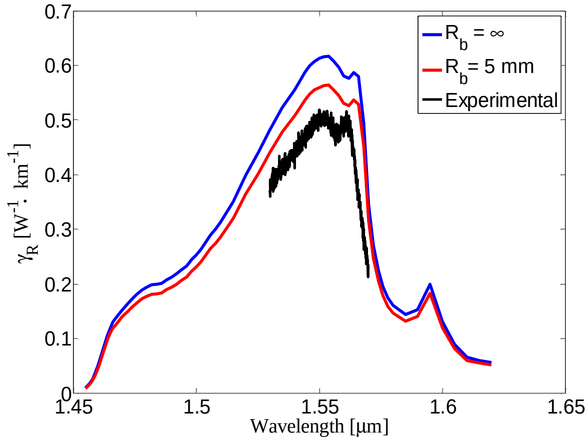


Fig. 5. The spectral variation of RGE for a HAF with and without bending. The solid black curve corresponds to experimentally measured RGE.

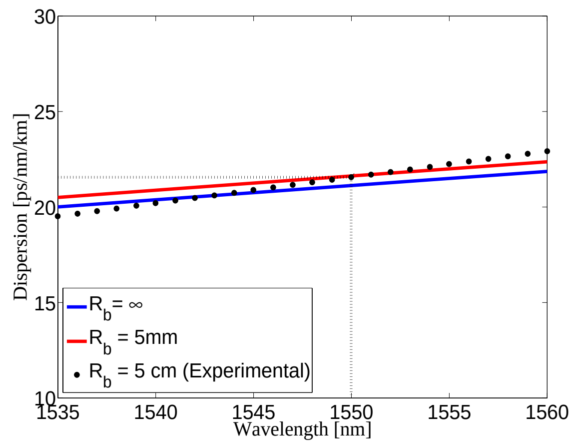


Fig. 6. The CD of a HAF with and without bending. The black dots resemble to the experiment, while solid lines stand for numerical computation.

Table 1. The experimentally characterized and numerically computed RGE and CD of a HAF.

Fiber characteristics	Theory		Experiment
	No bend	Bend (5mm)	(No bend)
CD [ps/nm/km] @1550 nm	21.16	21.63	21.56
RGE [W^{-1}. km^{-1}] @ 13.2 THz frequency shift	0.618	0.563	0.536

4. Conclusion

We have successfully measured the RGE and the CD of a HAF. The RGE was obtained by measuring the net Raman gain by pump on/off technique, whereas the CD of HAF was experimentally characterized by measuring the group delay using an optical network analyzer. It was found that the peak RGE was 0.536 W^{-1}. km^{-1} at a frequency shift of 13.2 THz, while the CD was 21.56 ps/nm/km at 1550 nm. A V-FEM was used to simulate the HAF in straight and bending cases. The influence of bending the HAF on its amplification and dispersion characteristics is observed and it is found that the RGE decreases while the dispersion increases when the HAF is bent into a smallest bending radius of 5 mm. In a summary, we can conclude that the numerical predictions from the theory are in good agreement with the experimental results.

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Appendix A

The RGE of a HAF is computed [3, 7, 16] as

$$\begin{aligned}\gamma_R &= \iint_S C_{\mathrm{SiSi}}(\Delta\nu)(1-2m(x,y))i_s(x,y)i_p(x,y)dxdy \\ &+ \iint_S C_{\mathrm{GeSi}}(\Delta\nu)2m(x,y)i_s(x,y)i_p(x,y)dxdy\end{aligned} \tag{A.1}$$

where i_s and i_p are the normalized signal and pump intensities obtained through an exact definition of Poynting vector [3] which is calculated by V-FEM. S is the PCF cross-section, $m(x, y)$ is the germanium concentration, and C_{SiSi} ($\Delta\nu$) and C_{GeSi} ($\Delta\nu$) are the Raman gain spectra of Si-O-Si and Ge-O-Si bounds [16] for a depolarized pump of 1455 nm. The peak C_{SiSi} and C_{GeSi} values are, respectively, $C_{\mathrm{SiSi,peak}} = 3.34 \times 10^{-14}$ m/W and $C_{\mathrm{GeSi,\ peak}} = 1.18 \times 10^{-13}$ m/W [3].