Raman Spectra of a PMMA Microstructured Optical Fiber and Direct Measurement of Its Gain Coefficient

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Abstract— A polymethylmethacrylate (PMMA) microstructured polymer optical fiber (mPOF) is fabricated and characterized. Using the cut-back technique the fiber loss is measured which is higher than the step-index silica fibers. Through a novel experimental scheme, the backward Stokes spectrum of the fabricated mPOF is recorded over a range exceeding 3000 cm^{-1} during the cut-back method and compared with that of step-index silica fiber. Especially, the gain coefficient of the Raman peak at 2950 cm^{-1} is directly measured, that is without comparing with other known material. The results show a very good agreement with those obtained through other experimental schemes.

KEYWORDS: Microstructured optical fibers (MOFs), polymer optical fibers (POFs), nonlinear optics, Raman and optical spectroscopy.

I. INTRODUCTION

Microstructured optical fibers (MOFs) guide light due to multiple rings of air holes around the core running along the entire length of the fiber. This enables processing of fibers using only a single material. After the fabrication of the first single-mode silica MOF in 1996 [1], various optical characteristic as a function of the microstructuring have been reported.

In recent years several alternative materials, other than silica, have been used in fabricating optical fibers. The aim is to extend the wavelength transmission range, increase the inherent nonlinearity for novel nonlinear applications or to increase the flexibility in designing and fabricating the fibers. Polymethylmethacrylate (PMMA) is one of such materials which is most commonly used for polymer optical fibers (POFs) [2]. POFs are more flexible and less brittle than silica glass optical fibers. The first single-mode microstructured polymer optical fiber (mPOF) made of PMMA was reported in 2001 [3]. The presence of a microstructure may result in a stronger light confinement and a smaller effective mode area, which would make mPOFs good candidates for nonlinear-optics applications [4]. In addition, PMMA mPOFs are easy to handle and therefore have a wide variety of applications such as illumination, sensing, high-speed data transmission, fiber optic components, etc [5]. Also, PMMA mPOFs have been reported to have intrinsically higher third-order susceptibility compared to that of silica [6]. However, mPOFs exhibit higher losses than silica fibers, resulting in a much shorter effective length. This trade-off between a strong nonlinearity and high losses has to be considered whenever evaluating fibers with respect to nonlinear applications. In this work we have evaluated mPOFs for application as Raman amplifiers.

Generally, for POFs and especially for mPOFs, very little work has been done in the context of Raman scattering. So far, the Raman gain coefficient of PMMA POFs was measured by means of an indirect method, i.e., by comparing the Raman gain spectra of PMMA with that of other known materials, e.g., toluene [7], [8]. In this work, we present the fabrication and characterization of an mPOF and for the first time, we directly measure its Raman gain coefficient based on a cut-back technique.

This paper is organized as follows: the fabrication and characterization of a PMMA mPOF are reported in section II. In section III, the theory of Raman scattering in optical fibers and the related equations are presented. The experimental setup used to record backward reflected Stokes spectrum of the fabricated mPOF over a range exceeding 3000 cm^{-1} is described in section IV. In section V, the measurements including the fiber loss and Stokes spectra for the mPOF and a step-index silica fiber are presented. Especially for the mPOF, the gain coefficient of the Raman peak at 2950 cm^{-1} is directly measured, that is without comparing with other known material. Finally, the paper is concluded in section VI with the remarks of our work.

II. Fabrication of the MPOF

Generally, a method which is used to fabricate mPOFs is based on a two-step process [9]. At first, a primary cylindrical preform with a diameter of 5-6 cm and a length of 8-10 cm is drilled with a desirable pattern based on the required application. The preform is then heated up gradually above the softening point of the PMMA in the oven of drawing tower. Subsequently, the softened preform is drawn which leads to a cane with a 6-mm diameter. The cane is sleeved into two polymer tubes with larger diameters to form a secondary preform which is put into the oven for the final drawing step. Fibers with the required parameters can be made by controlling the feed rate of the preform and the drawing rate of the fiber. This eventually is ended up with a fiber with an outer diameter of 125 μm.

Figure 1 shows a microscope cross section of the fabricated mPOF. The cladding of the fiber consists of an array of air holes with an average diameter of 4.2 μm, arranged in a triangular lattice consisting of 3 air-hole rings with a pitch of 6.6 μm and a hole-to-pitch ratio of 0.6. The effective mode area of the fiber is measured to be $A = 63.6\,\mu m^2$.

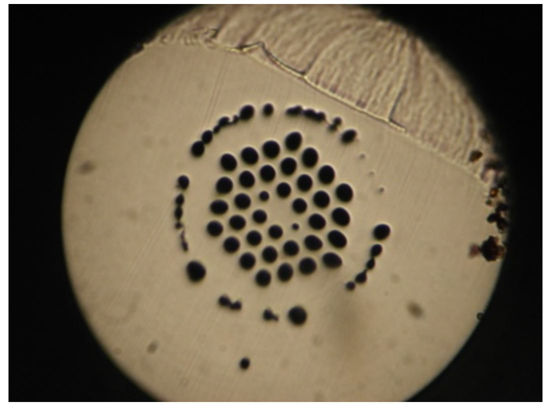

Fig. 1. Microscope cross-section image of the fabricated PMMA mPOF.

III. Raman Scattering in Optical Fibers

Light propagating through any material interacts with the molecules of the material. In a process so-called Raman scattering the power is transferred from one optical wave to another one with lower frequency due to the interaction with vibrations of molecules. The amount of frequency decrease is determined by the vibration modes. This process was first discovered in 1928 by Sir C.V. Raman, who was awarded the Nobel Prize in 1930 for his work on the Raman effect initially published in 1928 [10]. Experimentally, the incident light with the angular frequency ω_p serves as the pump wave which produces a radiation with a lower frequency ω_s called Stokes wave.

To record the generated Stokes power of the fiber, two different schemes can be used: a transmission scheme or a reflection scheme. In the transmission scheme, the Stokes wave emitted in the output end of the fiber (i.e. the opposite end as where the pump was launched) is measured. This scheme is mostly used for low loss optical fibers. On the other hand, the reflection scheme in which the Stokes wave emitted at the input end of the fiber, i.e. propagating in opposite direction as the pump, is better suitable for high loss fibers. Since the main focus of this article is on mPOFs which exhibit losses higher than those of silica fibers, our experimental setup was designed based on the reflection scheme.

The continuous wave (CW) propagation equation for the Stokes power P_s, propagating in the forward and backward direction is given by [11]:

$$\pm \frac{dP_s}{dz} = -\alpha_s P_s + g P_p P_s + g P_p h\nu_s B_0 \quad (1)$$

where α_s is the fiber loss at the Stokes frequency, P_p is the pump power, g is the Raman gain coefficient, ν_s denotes the Stokes frequency and B_0 the detector bandwidth (in units of Hz). The sign in front of the derivative on the left hand side accounts for the propagation direction of the scattered Stokes power. The first and the second terms in Eq. (1) correspond to the attenuation and the amplification of the Stokes power due to the fiber loss and Raman gain, respectively. The third term in Eq. (1) has been added to the corresponding equation for the stimulated Raman scattering. This is because in the experiment no seed or signal at the Stokes frequency was used to stimulate the process, and the only light wave used was the pump injected at $z = L$. Therefore, one can assume that the Stokes wave is built up spontaneously from the vacuum fluctuation photons located in a bandwidth as wide as the detector bandwidth B_0. In the calculation, the pump power was assumed to be undepleted: $P_p(z) = P_p(L)\exp(\alpha_p(z-L))$, where α_p is the loss at the pump wavelength while L is the fiber length. This means that we have assumed that the pump wave is mainly decreased due to the fiber loss and Stokes growth has little effect. This is a case, since the Stokes power is much lower than the pump power.

Before doing experiments, one should estimate the required fiber length through the simulation of the related equations. Figure 2 is obtained for a typical mPOF for two cases: a) transmission and b) reflection schemes. Fiber loss was assumed to be $\alpha = 5\,\text{dB/m}$ and detector band width to be $B_0 = 16\,GHz$. We have also assumed the Raman gain coefficient at the Stokes peak of 606.5 nm to be $g = 10\,(W.km)^{-1}$.

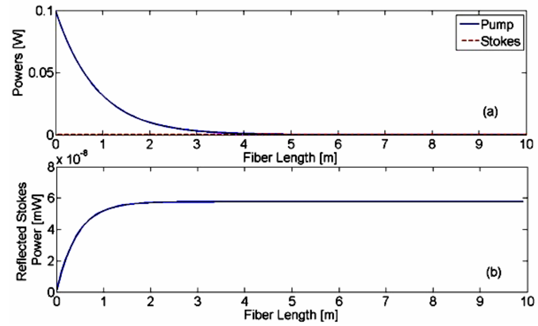

Fig. 2. The evolution of the pump and reflected Stokes powers along a typical mPOF as a function of different cut lengths for a) transmission, and b) reflection schemes.

As seen from Fig. 2 (a), for the transmission case, the pump power is decreased quickly due to the high fiber loss and negligible Stokes power is produced. For longer lengths, longer than effective length (~1m), this negligible Stokes power is more attenuated as it propagates down the fiber, since pump is not powerful and fiber loss is significant. Therefore, no power will be detected at Stokes wavelength at the output of the fiber. On the other hand, for Fig. 2 (b) there is an effective length, $\sim 1/\alpha$, beyond which the reflected Stokes power remains constant. This is the main advantage of the reflection scheme which is applicable to high loss fibers compared to the transmission one. Experimentally, to obtain the Raman gain coefficient of a fiber, one should choose a fiber with a length around its effective length, and then through the cut-back method, measure the reflected Stokes power for each fiber length. Based on Fig. 2 (b), the best curve which is fitted to the experimental data corresponds to a certain g, the Raman gain coefficient of the fiber. This scheme also enables the measurement of fiber loss at the pump wavelength during the cut-back method by collecting the transmitted pump power at the fiber output.

IV. EXPERIMENTAL SETUP

The experimental setup based on the reflection scheme is shown in Fig. 3. An Argon-ion laser (Spectra-Physics Stabilite 2017) with a wavelength of 514.5 nm serves as the pump laser (1). The output beam of the laser is incident on a dichroic mirror (4) after being reflected by two regular mirrors (2, 3). The dichroic mirror was adjusted to a specific angle so that it highly reflects the pump wavelength while transmitting light at other wavelengths. The reflected pump beam from this mirror is then injected to the fiber under test (FUT) through an objective lens (5). Due to the Raman scattering in the FUT, a small fraction of the pump power is back scattered at the Stokes wavelength and then passed through the objective lens and the dichroic mirror, respectively.

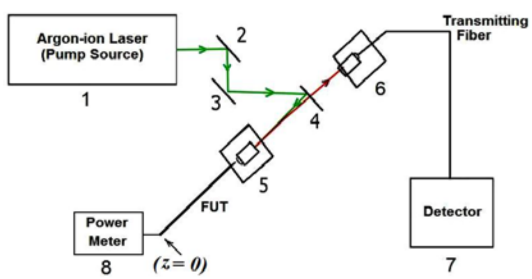

Fig. 3. Schematic illustration of the experimental setup used to measure the losses and Raman spectra of the fibers (here referred to as FUT, fiber under test). (1) CW pump laser; (2), (3) regular mirrors; (4) dichroic mirror at 514.5 nm; (5),(6) objective lenses; (7) detector for collecting spectra; (8) power meter for measuring the transmitted pump power.

After passing through another objective lens (6), the back-scattered Stokes light finally enters the collecting fiber and is transmitted to the detector (7). Depending on the power level of the reflected Stokes wave, as a detector we used an Ando AQ6315 optical spectrum analyzer (OSA) and a more sensitive spectrometer (Andor Technology SR-3031) for silica fiber and the mPOF, respectively.

V. RESULTS AND DISCUSSION

Measurements were done both on a silica fiber (SMF28) as well as the mPOF. In order to facilitate the comparison of the collected spectra for both fibers, a short silica fiber ($\sim 2m$) was chosen. The mPOF length was about its effective length, $\sim 1m$, which was already estimated through Fig. 2(b). Moreover, since the softening point of PMMA is approximately 10 times lower than that of silica, the measurements on the mPOF were performed at a lower pump power, in order not to deform its microstructure. Figure 4 shows the two spectra measured in counts, recorded by the Andor spectrometer. As it is evident, the intensity level of the spectrum of the scattered light for the silica fiber is higher than that of the mPOF. This is due to the lower losses exhibited by silica. As for the silica fiber, the measurement shows a main Stokes shift of 526.5 nm (440 cm^{-1}) whereas the main Stokes shift for the mPOF equals 606.5 nm (2950 cm^{-1}). The peak located at 514.5 nm arises from the residual pump power reflected back from the FUT. Both spectra are in good agreement with the spectra of non-microstructured step-index fibers recorded by using different methods [8], [12].

From the cut-back measurements of the mPOF, the fiber loss and the input pump power were obtained. With this approach, the loss of the silica fiber was measured to be $\alpha = 17.4\ dB/km$ [13] and of the mPOF to be $\alpha = 5\ dB/m$. It is noted that due to imperfections in the structure of the mPOF, the losses of the mPOF are higher than the material loss of pure PMMA which is about $0.01 dB/m$ [14]. Moreover, the finite number of air-holes in the fiber cross-section leads to high confinement losses of the mPOF which means that all the guided modes are leaky.

Since the Raman scattering of the mPOF is most pronounced at longer wavelengths, several Raman spectra were recorded around the main peak, 606.5 nm (2950 cm^{-1}), each one corresponding to a different fiber length. This is shown in Fig. 5. Only those spectra which correspond to lengths within the effective length of the fiber are plotted. An Andor spectrometer was used to record the spectra. As it is seen, for a longer fiber, a higher back-scattered Stokes intensity is obtained. However, as shown in Fig. 2(b), when the fiber reaches its effective length ($\sim 1m$), the Stokes intensity saturates which is due to the high pump power attenuation.

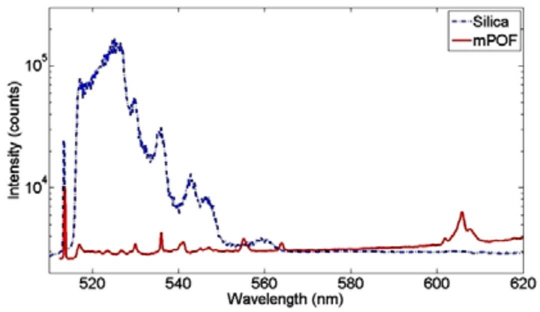

Fig. 4. Raman spectra of the silica fiber and the mPOF pumped and recorded by 514.5 nm Argon-ion laser and Andor spectrometer, respectively.

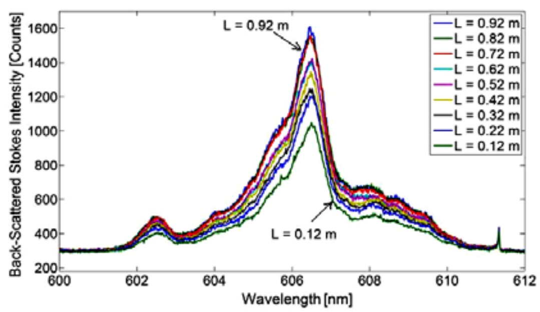

Fig. 5. Raman spectra around the main peak, 606.5 nm for the mPOF recorded for different lengths within the effective length.

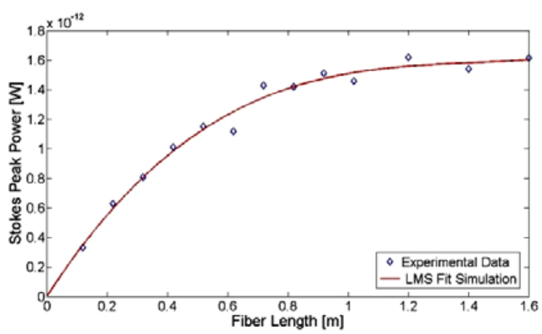

Fig. 6. Stokes powers of the mPOF for the main peak, 606.5 nm as well as the least mean square (LMS) fit simulation for different fiber lengths.

Figure 6 shows the power of the 606.5 nm Stokes peak, as a function of length. In the same figure, a least mean square (LMS) fit is also plotted. This is obtained by solving the Eq. (1) for the Stokes power P_s, and the corresponding relation for the pump power P_p. As in Fig. 5, the saturation of the Stokes power can be seen at longer fiber lengths beyond the effective length.

The Raman gain coefficient was determined by using the least mean square method to fit the predicted reflected Stokes power to that obtained from the measurements. In other words, we used Eq. (1) and adjust the value of g using the LMS method to get the best fit. In our calculation, we took into account that a small fraction of the pump power was reflected at the output-end of the fiber ($z=0$) due to Fresnel reflections. This was done by adding $P_p^R(z) = RP_p(z=0)\exp(-\alpha_p z)$, to the pump power in Eq. (1), where R is the Fresnel power reflection coefficient. The parameters used for our calculations are $P_p(L) = 68\,mW$, $\alpha_s \approx \alpha_p = 5\,dB/m$, and $B_0 = 16\,GHz$ (at 606.5 nm). As a result, the Raman gain coefficient at the main peak for the mPOF is found to be $g = 12.5(W.km)^{-1}$. Similarly using the SMF28, for the main peak we measured the silica Raman gain coefficient of $g = 2.5(W.km)^{-1}$. Our results are in good agreement with those of other works which utilize comparison between the Raman response of polymer fibers to that of the toluene [7], [8].

VI. Conclusion

We have fabricated and characterized a PMMA mPOF and reported its Raman spectra when excited by a 514.5 nm Argon-ion laser. The spectrum shows a main peak at 2950 cm^{-1} while a silica fiber has a main peak at 440 cm^{-1}. The losses and Raman gain coefficient of the mPOF were measured to be $\alpha = 5\,dB/m$ and $g = 12.5(W.km)^{-1}$, respectively. To the best of our knowledge, this is the first time that the Raman gain coefficient in a PMMA mPOF is directly measured. The results show a very good agreement with those obtained through other experimental schemes.

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(No photo available)

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