Effect of a Nonlinear Photonic Crystal Fiber on the Noise Characterization of a Distributed Raman Amplifier

Chun-Liu Zhao, Zhaohui Li, Xiufeng Yang, Chao Lu, Wei Jin, and M. S. Demokan

***Abstract*—The first experimental study of the effect of a nonlinear photonic crystal fiber (PCF) on the noise characteristics of a distributed backward-pumped Raman amplifier is reported. The PCF has a highly nonlinear Raman efficient, and a high Rayleigh scattering parameter. When an optical signal first passes through a 100-m nonlinear PCF followed by a 25-km single-mode fiber, the optical signal-to-noise ratios (OSNRs) of the amplified spontaneous emission and the double Rayleigh scattering (DRS) are improved because the high Raman gain efficiency of the PCF makes the Raman gain of the signal at the beginning of the link increase, and the signal power over the length of the transmission becomes near a constant. However, the improvement of the OSNR of DRS compared with the OSNR of amplifier spontaneous emission is limited by the large Rayleigh scattering in the PCF.**

***Index Terms*—Amplified spontaneous emission (ASE), double Rayleigh scattering (DRS), photonic crystal fiber (PCF), Raman amplifier.**

I. INTRODUCTION

A DISTRIBUTED fiber Raman amplifier, which uses the transmission fiber as the gain medium, is considered to be a key component in realizing the next-generation photonic networks because of its features of low noise, flexible gain bandwidth, and simple configuration. Over the transmission length (of the order of kilometers), significant double Rayleigh scattering (DRS) of the signal and amplified spontaneous emission (ASE) inside the amplifier occurs [1]–[4]. These phenomena will appear as noise and they will degrade the amplifier performance. Recently, studies on minimizing the combined effect of Raman ASE, DRS, and nonlinearity were reported [5], [6]. The key is to balance gain and loss at every point in the fiber, making the signal power constant over the length of the fiber [7], [8]. By optimizing the pumping schemes and transmission fiber properties, Raman ASE and DRS can be stabilized.

Meanwhile, a new type of fiber, called the holey fiber, which is a category of photonic crystal fibers (PCFs), has been used in Raman amplifiers as the gain medium [9], [10]. Such fibers consist of a pure silica core surrounded by a regular array of longitudinal air holes and can offer tight modal confinement, thus, can provide an effective nonlinearity per unit length which can be an order or more higher than that of a conventional fiber. Their Raman efficiency, defined as the Raman gain coefficient divided by the pump effective area, is expected to be much higher than that of a standard single-mode fiber (SMF). In this letter, we report the first experimental study of the effect of a nonlinear PCF on the noise characteristics of a distributed Raman amplifier. In our experiment, a piece of nonlinear PCF with a length of 100 m is inserted in a backward-pumped distributed Raman amplifier. When an optical signal is transmitted along a 100-m nonlinear PCF and 25-km SMF, the OSNRs of both the ASE and the DRS increase. The first reason is because the signal Raman gain is increased at the beginning of the transmission when the signal passes through the nonlinear PCF. The second is that the PCF with high gain efficiency, when placed before the SMF, makes the signal power excursion small, and the signal power becomes nearly constant over the transmission length. However, the OSNR of the DRS is not improved as much as the OSNR of the ASE, because of the larger amount of Rayleigh scattering in a nonlinear PCF than that in SMF.

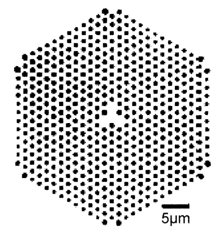

Fig. 1. Transverse structure of the highly nonlinear PCF.

II. PROPERTIES OF THE HIGHLY NONLINEAR PCF

The PCF used in our experiment is the hybrid-core nonlinear dispersion-shifted PCF (zero chromatic dispersion wavelength at 1500 nm, and dispersion of ~5 ps/nm/km at 1550 nm) fabricated by Crystal Fiber A/S. The hybrid core region comprising a germanium-doped center element ($n = 1.487$) surrounded by three fluorine-doped regions ($n = 1.440$) is embedded in a standard triangular air–silica cladding structure, as shown in Fig. 1. The diameter of the doped elements equals the pitch ($\Lambda = 1.5\ \mu$m). The effective area $A_{\rm eff}$ of the fundamental mode is about 3.46 μm^2. The nonlinear coefficient γ of the guided mode in this fiber is measured at 1555 nm by use of a direct continuous-wave measurement of the nonlinear phase shift

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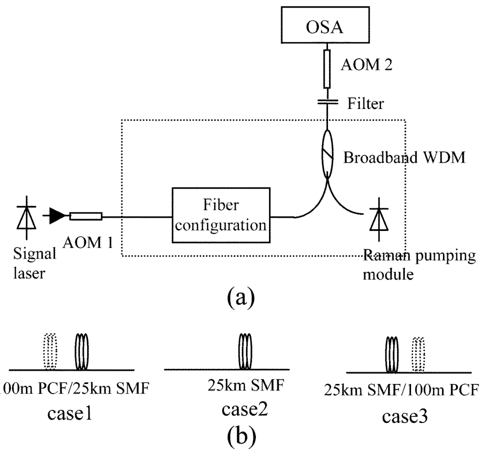

Fig. 2. (a) Experiment setup. (b) Fiber configuration.

suffered by a beat signal propagating in the fiber. The measurement procedure is fully described in [11]. From the measured nonlinear phase shift versus the launched optical power, we obtain a value of $\gamma = 11\ \mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$, which is about five times higher than that of a conventional dispersion-shifted fiber.

Rayleigh scattering, which is another important phenomenon, occurs simultaneously. Rayleigh scattering in conventional fibers arises from the light interacting with a material having uneven density. Variations in material density and compositional fluctuations occurring during fiber manufacture create random inhomogeneities that give rise to refractive index variations. In PCFs, in addition to density and compositional fluctuations, Rayleigh scattering also arises from structure fluctuations because the geometry of the holes may not be perfectly regular. Here, we use an optical time-domain reflectometer (OTDR) with pulses of 5-ns duration to measure the Rayleigh scattering of the nonlinear PCF. Backscattering parameter k ($k = S \cdot \alpha_s$, where S is the fraction of the light scattered in all directions that is captured by the fiber core and guided back to the OTDR, and α_s is a scattering attenuation coefficient per unit length) is about 1.4×10^{-3} /km at wavelength 1560 nm. It is up to one order higher than that in a conventional SMF. Because the PCF has different optical characteristics from the SMF, such as a highly nonlinear Raman coefficient, and a high Rayleigh scattering parameter, distributed Raman amplifier obtained by using a PCF and an SMF can be significantly different from that obtained by using a conventional fiber alone.

III. Effects of the PCF on the Distributed Raman Amplifier

Fig. 2 shows the apparatus used to measure noise characterization of a backward-pumped distributed Raman amplifier. Acoustooptic Modulator 1 (AOM1) generates a modulated signal, and Acoustooptic Modulator 2 (AOM2) provides an optically gated receiver. These switches have an extinction ratio of greater than 90 dB operating at a modulation frequency of 200 kHz. The duty cycles of the signal and the receiver are 50%. The input signal power is 0 dBm, and the wavelength is 1550 nm.

As demonstrated in [2], the signal output power is measured when the receiver and the signal are in phase. The Rayleigh scattered signal and the ASE is measured as a sum (the total noise power) with the receiver sampling window out of phase with the signal. The Rayleigh scattered power appears as a narrow spectral peak on the background ASE level observing through an optical spectrum analyzer. The change in the ASE level can be ignored when the input signal is turned ON or OFF, because only one small signal transmits through the Raman amplifier. Here, the ASE power is measured conveniently by turning OFF the signal. So the Rayleigh scattered noise is given by subtracting the ASE power from the total noise power. Because the spectral range of the ASE is about 10 THz, in order to measure the noise in the signal channel band, we use an optical filter (center wavelength 1550 nm, and passband 1.5 nm) at the transmission end.

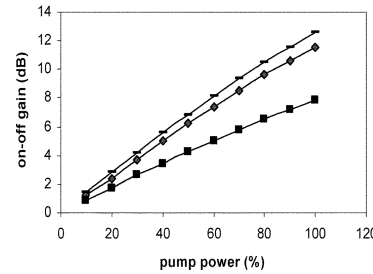

Fig. 3. ON–OFF gain as a function of the pump power in Raman amplifiers. ▬: case1 (PCF+SMF). ♦: case2 (SMF). ■: case3 (SMF+PCF).

The Raman pump module in Fig. 2 is formed by two wavelength- and polarization-multiplexed lasers. We optimize the pump power ratios in order to obtain flat output signal power across the C-band. A broad-band wavelength-division multiplexing is used to multiplex the pump and the signal. The fiber in which Raman gain is observed is an SMF of 25-km length. In order to observe the effect of the PCF on the Raman amplifier, a 100-m highly nonlinear PCF, whose ends are tapered, is coupled to either the front end of a 25-km SMF (case1), or to the back end of the SMF (case3). In other words, in case1, the transmission medium consists of first the PCF then the SMF; in case2, only the SMF; in case3, first the SMF then the PCF. The noise characterization for the three cases of transmission link have been measured.

Fig. 3 shows the ON–OFF gain for the three cases as a function of pump power in the distributed Raman amplifiers. The ON–OFF gain obtained at a certain pump power is strongly dependent on the position of the PCF. At pump power 70 mW (10% of the maximum pump power), the ON–OFF gains for the three cases are 1.4, 1.2, and 0.9 dB for case1, case2, and case3, respectively. With increasing pump power, the difference of the ON–OFF gains for the three cases becomes large, and the slopes of the ON–OFF gain versus pump power have been measured to be 0.125, 0.116, and 0.078, respectively. Thus, at maximum pump power, the ON–OFF gains for three cases are 12.57, 11.55, and 7.88 dB, respectively. Compared with case2, the pump efficiency for case1 is improved because the length of the Raman gain medium is increased by inserting the PCF before the SMF, and the residual pump power after the SMF is utilized completely. In theory, the closer the highly nonlinear fiber is placed to the span end, the higher the pump efficiency becomes because the pump light is intense in the highly nonlinear fiber due to its large Raman gain efficiency [7]. In case3, however, the pump efficiency is not improved by moving the PCF to the span end, i.e., the farthest point from the signal laser. The largest ON–OFF gain for case3 is 7.88 dB, which is about 3.6 dB smaller than that for case2 (only the SMF). This is mainly caused by the large

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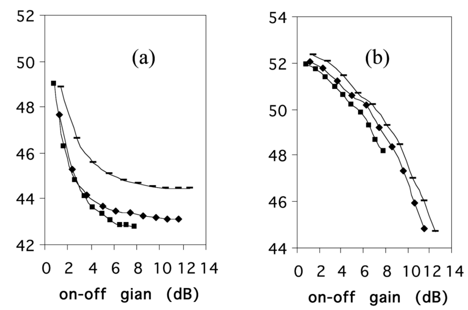

Fig. 4. OSNRs in Raman amplifier (a) OSNR of ASE, (b) OSNR of DRS. ▬: PCF+SMF. ♦: SMF. ■: SMF+PCF.

insertion loss (about 1 dB) of the PCF at the pump laser wavelengths. The pump power after the PCF is reduced dramatically, and the pump power injected into the main Raman gain medium (the SMF) is lower than that in case2. Even though the PCF has large Raman gain efficiency, the large insertion loss at the pump wavelength causes impairment.

Fig. 4 shows the optical signal-to-noise ratio (OSNR) of the ASE ($\mathrm{OSNR}_{\mathrm{ASE}}$), and the OSNR of the DRS ($\mathrm{OSNR}_{\mathrm{DRS}}$) plotted against the ON–OFF gain of the Raman amplifier in the three cases. When the PCF is inserted before the SMF (case1), both the $\mathrm{OSNR}_{\mathrm{ASE}}$ and the $\mathrm{OSNR}_{\mathrm{DRS}}$ are higher than the OSNRs for case2 (only the SMF). The $\mathrm{OSNR}_{\mathrm{ASE}}$ and the $\mathrm{OSNR}_{\mathrm{DRS}}$ increases by about 1.4 and 0.4 dB respectively, when at the ON–OFF gain is 6.2 dB. For a Raman amplifier only using SMF, $\mathrm{OSNR}_{\mathrm{ASE}}$ can be improved to a certain extent by increasing the signal input power or pump power in a certain range of signal input power and pump power; otherwise, an improvement of the $\mathrm{OSNR}_{\mathrm{DRS}}$ cannot be achieved only by increasing the signal input power because the ratio between the DRS light and the signal is independent of the signal input levels [4]. At the beginning of the transmission link, the OSNR is largest, while the pump power is lowest. An ideal distributed Raman amplifier is obtained by balancing the gain and the loss at every point in the fiber. The most important change which occurs when the highly nonlinear PCF is placed in the fiber link is that of the distribution of optical signal along the fiber link. In case2, only the SMF is used as the Raman gain medium. The Raman gain of the signal at the beginning of the link is lowest. When the PCF is placed before the SMF (case1), the situation is changed. The Raman gain of the signal at the beginning of the link is high because of the high Raman gain efficiency of the PCF. The nonuniformity of the Raman gain distribution in the fiber is amended. A theoretical analysis on the Raman gain distribution of the fiber span is significant, and will be presented in the near future. In Fig. 2(b), the configuration of case1 (PCF+SMF) is analogous to the negative ($-D$) and positive ($+D$) dispersion-managed fiber Raman amplifier in [7]: The placing of the PCF before the SMF makes the signal power nearly constant over the length of the transmission. The larger power dip in the middle of the span results in lower OSNRs at the output end. Thus, the large OSNRs in case1 are achieved because the signal power excursion is small. The magnitude of DRS noise during the transmission increases because of large Rayleigh scattering in the PCF. This causes the $\mathrm{OSNR}_{\mathrm{DRS}}$ to increase by only 0.4 dB as compared to case2.

When the PCF is moved to the end of the SMF (case3), the $\mathrm{OSNR}_{\mathrm{ASE}}$ and the $\mathrm{OSNR}_{\mathrm{DRS}}$ decreases by about 0.5 and 0.7 dB, respectively, for an ON–OFF gain of 6.2 dB as compared to case2. This can be explained as follows: When a highly nonlinear (PCF) fiber is inserted at the end of the transmission link of a backward-pumped Raman amplifier, the pump laser power will be highest in the nonlinear fiber. Because of the large Raman gain coefficient of the nonlinear fiber, the imbalance in the signal power over the length of the transmission is aggravated further than that in case2. This causes both the $\mathrm{OSNR}_{\mathrm{ASE}}$ and $\mathrm{OSNR}_{\mathrm{DRS}}$ to decrease. As shown in Fig. 4(b), the decrease in the $\mathrm{OSNR}_{\mathrm{DRS}}$ is larger than that in the $\mathrm{OSNR}_{\mathrm{ASE}}$. The reason is that the DRS appear at the same spectral region as the signal and the DRS noise power increases in proportion to the signal power. When the PCF with high Rayleigh backscattering is placed at the end of the transmission, the impact of DRS becomes stronger [7].

IV. Conclusion

The OSNR of the distributed backward-pumped Raman amplifier will be improved when a piece of highly nonlinear PCF is inserted at the beginning of the link. Because of the high Raman gain efficiency of the PCF, the Raman gain of the signal at the beginning of the link increases even when the pump power is not large. Moreover, the power excursion of the signal over the length of the transmission is reduced. Thus, a large OSNR is achieved by placing the PCF before the SMF. As compared to just having an SMF, the $\mathrm{OSNR}_{\mathrm{ASE}}$ is improved by about 1.4 dB, while the improvement in the $\mathrm{OSNR}_{\mathrm{DRS}}$ is about 0.4 dB. The improvement in $\mathrm{OSNR}_{\mathrm{DRB}}$ is limited because the PCF has large Rayleigh scattering.

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