Numerical analysis of Raman amplification and optical signal-to-noise ratio in a photonic crystal fiber

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A numerical design on the triangular photonic crystal fiber (PCF) based backward multi-pump Raman amplifier is presented. It is demonstrated that high flat Raman gain can be reached based on PCF. Influences of different geometric parameters and germanium doping concentrations on the Raman net gain, amplified spontaneous emission (ASE) noise and double Rayleigh backscattering (DRBS) of the signal have been analyzed. For optimizing crystal fiber Raman amplifier (FRA), there is tradeoff between the geometric parameter and germanium doping concentration of triangular PCF. The results show that PCF is an appropriate candidate for high gain Raman amplifiers.

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Distributed Raman amplifiers (DRAs) with broad bandwidth and low optical noise for high-capacity, long haul wavelength division multiplexing (WDM) transmission systems have been investigated extensively[1,2]. Recently, a new kind of Raman gain medium, the photonic crystal fibers (PCFs) have become attractive. Transverse section of the PCF usually consists of a silica core surrounded by a regular array of longitudinal air holes and can offer tight modal confinement. Figure 1 shows one of the structures called triangular PCF, where d is the air-hole diameter and Λ is the pitch. The GeO_2 doped area is actually the area surrounded by the most inner air-hole ring[3], whose radius is $\Lambda - d/2$, so the high GeO_2 concentration can be obtained by using very large air-fraction cladding, i.e., closely spaced large air holes. Through careful design of the core GeO_2 concentration and geometric parameters, the PCF can provide higher Raman efficiency than that of a standard single-mode fiber (SMF)[3,4]. So far, Raman amplifier based on different structures of PCF have been studied on some aspects of the system performances experimentally[5] or theoretically[6,7]. Though some of the key parameters, such as the coupling efficiency with conventional SMF, fiber attenuation coefficient and Rayleigh backscattering (RBS) coefficient, are still not qualified enough, great improvement can be expected[8]. In particular, further reduction of the RBS coefficient and the background loss, which strongly affects pump efficiency and optical signal-to-noise ratio (OSNR), can greatly enhance the Raman efficiency with respect to conventional fibers.

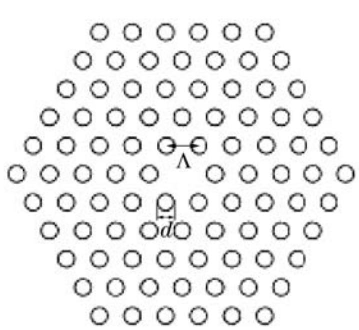

Fig. 1. Transverse section of a PCF with triangular lattice.

The performances of triangular PCF-based Raman amplifiers employing multiple pumps are studied in this paper. The dependence of parameters, such as the Raman net gain, OSNR of the amplified spontaneous emission (ASE) ($OSNR_{ASE}$), and OSNR of double Reyleigh backscattering (DRBS) ($OSNR_{DRBS}$), on the geometric parameter and germanium doping concentration of the triangular PCF are investigated. Simulation results are presented and comparisons are carried out to verify the analysis.

A mathematical model was given in Ref. [9] for multi-pump fiber Raman amplifier (FRA) based on a set of propagation equations which described the forward and backward power evolutions of pumps, signals, noise, and signal RBS along the fiber. The model includes the stimulated Raman scattering (SRS) and its amplification, the spontaneous Raman emission and its temperature dependence, the RBS, the fiber attenuation, and the interaction among pumps, signals, noise and signal RBS from either propagation directions. Because PCF presents large RBS coefficient and fiber attenuation coefficient, the related noise performances should be considered. In the equations, the contribution to the noise due to the RBS of the signals has been distinguished from the other noise components in order to evaluate the negative impacts of DRBS of signal and OSNR of ASE on the RFA performances, respectively. The DRBS of signal increases in proportion to the signal power, therefore the multi-path interference can be created to increase the bit error rate in the receiver[10]. We evaluate the negative effect of the DRBS on the signal at the wavelength λ_i by the ratio of the signal power $P^+(\lambda_i)$ to the signal RBS power $n^+_{\mathrm{SRB}}(\lambda_i)$ at the PCF end,

$$\mathrm{OSNR}_{\mathrm{DRBS}}(\lambda_i) = 10\log_{10}\left[\frac{P^+(\lambda_i)}{n^+_{\mathrm{SRB}}(\lambda_i)}\right]. \quad (1)$$

We solved the propagation equations using fifth-order

Runge-Kutta method with step size control. For numerical stability, the mesh size of the fiber length Δz was chosen as 50 cm and the maximum Raman medium length was 50 km. The noise wavelength bandwidth $\Delta\lambda$ is 1 nm and room temperature T is considered. Three backward pumps at 1457, 1484 and 1494.5 nm with a total input power of 780 mW are employed, which bring about Raman amplification at L-band. The composite Raman gain is expressed as the logarithmic sum of individual Raman gain by each pump with a weighting factor[2].

In the simulation, low-loss single-mode PCF with two kind of geometric parameters are used, one is with $d/\Lambda = 0.44$ at $\Lambda = 4.2$ μm and the other is with $d/\Lambda = 0.44$ at $\Lambda = 3.2$ μm[11]. For each geometric parameter, two different GeO_2 concentrations, 0% and 19.3%, are considered[3,9]. The related parameters are listed in Table 1. We used the experimentally measured PCF attenuation coefficient as a function of various wavelengths in Ref. [11], and assumed that the measured PCF attenuation coefficient is independent of the germanium doping concentration. The RBS coefficient versus signal wavelength was reported in Refs. [3,9—11]. In particular, the RBS coefficient of PCF with 3.2-μm pitch is almost 3.2 times that of PCF with 4.2-μm pitch when d/Λ is fixed.

Figure 2 shows the Raman net gain of the PCFs. Under the assumption that attenuation coefficient is independent of the germanium concentration, the figure shows that the Raman net gain depends strongly on GeO_2 concentration when the geometric parameters are fixed. For example 19.3% GeO_2 concentration with $\Lambda = 4.2$ μm produces an extra gain of about 9.35 dB. It is also shown that with the same GeO_2 doped concentration and d/Λ value, when the air-hole pitch changes form 4.2 to 3.2 μm, the net gain reduces inversely in spite that Raman gain coefficient increases. The decreases are about 2.26 dB for 19.3% GeO_2 doping concentration and 2.47 dB for pure-silica core. It is mainly caused by the increase of the fiber attenuation coefficient when the air-hole pitch reduces.

Table 1. Parameters Used in the Single-Mode PCF (the Reference Pump Wavelength λ_{ref} is 1455 nm and PCF Length L is 6.5 km)

Λ (μm)	GeO_2 Concentration (%)	Peak Raman Gain Coefficient, γ_R ($W^{-1}\cdot km^{-1}$)	Raman Effective Area, A_{eff} (μm^2)
3.2	0	2.2	15.5
3.2	19.3	5	
4.2	0	1.33	25
4.2	19.3	3.28	

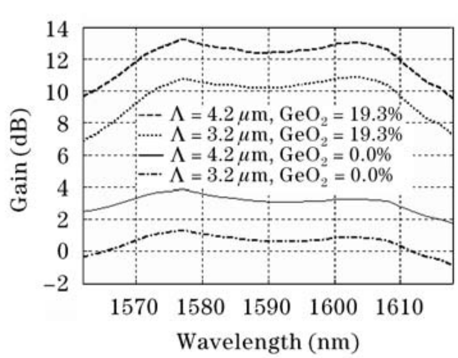

Fig. 2. Net gain versus signal wavelength for the two triangular PCFs with $d/\Lambda = 0.44$, $\Lambda = 3.2$ and 4.2 μm, respectively, for different GeO_2 concentrations.

$OSNR_{DRBS}$ describes the influence of the signal DRBS on the triangular PCF-based multi-pump Raman amplifier, and $OSNR_{ASE}$ describes the influence of ASE noise. Figure 3 gives the $OSNR_{DRBS}$ and $OSNR_{ASE}$ (considering single- and double-Rayleigh backscattering of ASE) in respect to the pitch parameters and the GeO_2 doping concentration, respectively. It is noticed that $OSNR_{DRBS}$ and $OSNR_{ASE}$ become lower when the ratio d/Λ and pitch Λ are fixed and the GeO_2 doping concentration increases. For example at 1580 nm, the $OSNR_{DRBS}$ and $OSNR_{ASE}$ are 57.48 and 32.41 dB for pure-silica PCF with $d/\Lambda = 0.44$, $\Lambda = 4.2$ μm, decreases of 16.87 and 16.55 dB occur for 19.3% GeO_2 doping concentration. The reason is that the RBS coefficient $r(\lambda_i)$ increases quickly along with the enhancement of GeO_2 doping concentration. It is also noticed that, when the pitch decreases, the attenuation coefficient $\alpha(\lambda_i)$ and the RBS coefficient $r(\lambda_i)$ also increase, which gives more negative contribution to the $OSNR_{DRBS}$ and $OSNR_{ASE}$, in spite that the Raman gain coefficient γ_R increases mainly due to decrease of the effective area A_{eff}.

It can be seen that the influence of the geometric parameter and GeO_2 doped concentration is complicated. They result in the change of Raman gain coefficient, fiber attenuation coefficient and RBS coefficient, which jointly affect the performance of FRA. In other words, higher Raman net gain does not always go with better $OSNR_{DRBS}$ and $OSNR_{ASE}$. If the fabrication process provides further $\alpha(\lambda_i)$ and $r(\lambda_i)$ reductions, a tradeoff between these two coefficients and the PCF Raman gain coefficient design can be found.

In order to verify our simulations, comparisons with amplifiers based on PCF[6] are carried out. For example, for the similar parameters ($d/\Lambda = 0.625$, $\Lambda = 4$ μm, pump power of 1 W and fiber length of 9 km), the simulated results in Ref. [6] showed the net gain of about 12 dB and bandwidth of about 20 nm. Our simulation analysis has shown the same gain level, and the bandwidth increases to more than 40 nm due to employing multiple pumping (see Fig. 2 and Fig. 2(a) in Ref. [6]). While the

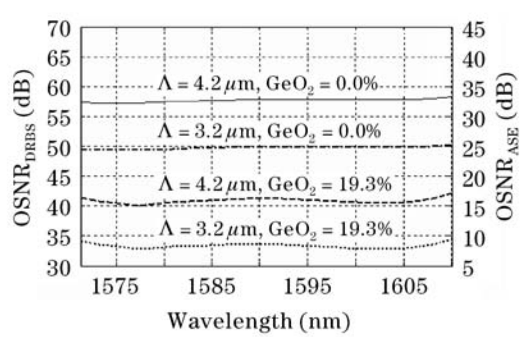

Fig. 3. $OSNR_{DRBS}$ and $OSNR_{ASE}$ versus signal wavelength for the two triangular PCFs with $d/\Lambda = 0.44$, $\Lambda = 3.2$ and 4.2 μm, respectively, for different GeO_2 concentrations.

DRBS of the signal is also in the same level (see Fig. 3 and Fig. 2(b) in Ref. [6]).

In conclusion, triangular PCF-based backward multi-pump Raman amplifiers have been analyzed by numerical simulation. Using two different geometric parameters with two GeO_2 doping concentrations, the Raman net gain, $OSNR_{ASE}$ and $OSNR_{DRBS}$ are simultaneously investigated. Results show that an increase of the attenuation coefficient $\alpha(\lambda_i)$ dramatically reduces the Raman net gain. Meantime, the RBS coefficient and $\alpha(\lambda_i)$ also dramatically reduce these two kinds of OSNRs. For optimizing Raman net gain, $OSNR_{ASE}$ and $OSNR_{DRBS}$, an eclectic control of geometric parameters as well as germanium doping concentration is required.

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References

1. H. Kidorf, K. Rottwitt, M. Nissov, M. Ma, and E. Rabarijaona, IEEE Photon. Technol. Lett. **11,** 530 (1999).
2. S. Namiki and Y. Emori, IEEE J. Sel. Top. Quantum Electron. **7,** 3 (2001).
3. M. Fuochi, F. Poli, S. Selleri, A. Cucinotta, and L. Vincetti, J. Lightwave Technol. **21,** 2247 (2004).
4. Z. Yusoff, J. H. Lee, W. Belardi, T. M. Monro, P. C. Teh, and D. J. Richardson, Opt. Lett. **27,** 424 (2002).
5. C. J. S. de Matos, K. P. Hansen, and J. R. Taylor, Electron. Lett. **39,** 424 (2003).
6. M. Bottacini, S. Selleri, F. Poli, A. Cucinotta, and M. Foroni, in *Proceedings of LEOS 2004* 645 (2004).
7. S. K. Varshney, K. Saitoh, and M. Koshiba, IEEE Photon. Technol. Lett. **7,** 2062 (2005).
8. K. Nakajima, J. Zhou, K. Tajima, K. Kurokawa, C. Fukai, and I. Sankawa, J. Lightwave Technol. **23,** 7 (2005).
9. M. Bottacini, F. Poli, A. Cucinotta, and S. Selleri, J. Lightwave Technol. **22,** 1707 (2004).
10. J. Bromage, J. Lightwave Technol. **22,** 79 (2004).
11. L. Farr, J. C. Knight, B. J. Mangan, and P. J. Roberts, in *Proceedings of ECOC-IOOC* PD 1.3 (2002).