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Investigation of Raman Amplification In Photonic Crystal Fibers

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Abstract

In this paper, Raman amplification characteristics in photonic crystal fibers (PCFs) are investigated in details. Performance comparsion between PCF-based Raman amplifier and other conventional fiber-based counterparts is presented. The simulated results reported here can be used as a guide line to design PCF-based Raman amplifier that outperforms the conventional fiber amplifiers. Raman gain as high as 33 dB can be obtained with a well designed PCF even at low pump power of 300 mW.

1. Introduction

The real requirement to compensate the suffering losses that optical signals face them, during the transferring from the transmitter to the receiver devices, leads to demonstrate many types of optical amplifiers. Fiber Raman amplifier (FRA) employs the properties of silica fiber to obtain the required amplification of the signal based on stimulated Raman scattering process (SRS), see Fig. 1. Here SRS occurs when a sufficiently high pump power of shorter wavelength is lunched into fiber with small power signal of longer wavelength. The SRS causes transferring of energy to the signal of the longer wavelength with small energy difference release as phonos. The FRA is becoming progressively important in optical systems due to its relevant features [1,2]: High fibers Raman gain can be achieved with relatively low loss. The Raman gain is nonresonant where the spectrum can be adjusted by suitable choosing of the pump wavelengths, Small polarization mode dispersion due to the reduced number of components. Raman gain exists in every fiber, which provides cost effectiveness. It has been demonstrated that the PCF greatly enhance nonlinear effects, and therefore represent an optimal solution as fiber Raman amplifier.

Recently photonic crystal fibers (PCFs) have appeared as a new class of optical fibers, which have attracted large scientific and commercial interest during the last years. The PCFs are single material fibers, usually in silica, with a large number of air holes located in the cladding region of the fiber [3,4], like that shown in Fig. 2. The shape, size, and distribution of holes can be controlled or designed, which allows for PCFs to have unusual properties that cannot be achieved with conventional fibers. In order to design photonic crystals, there are some crystal parameters that must be engineered,

a- Dimensionality: The PCs can be one-, two- or three- dimensional lattices depending on the periodicity of the refractive index which determines the dimensionality of the PCs.

b- Lattice parameter pitch (Λ): which is the distance between the centers of the air holes, as shown in Fig. 2..

c- Air hole diameter (d).

d- Refractive index contrast: This value offers a general idea of the scattering strength of the PCs. The ability to design and change these parameters enable PCs to possess numerous unusual properties, including highly tunable dispersion, high nonlinearity and, single mode operation at all wavelengths [5].

This paper addresses the characteristics of Raman amplification in PCFs

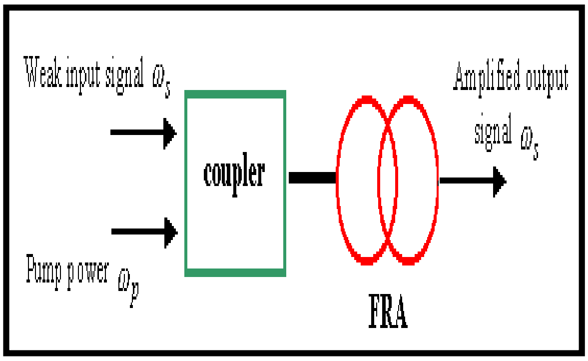


Fig. 1. Fiber Raman amplifier

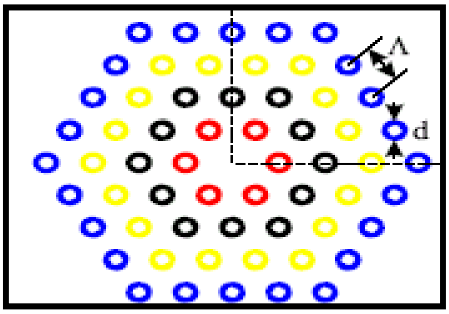


Fig. 2. Hole pitch (Λ) and hole diameter (d) of PCFs

2. THEORY

2.1. Raman Amplifier Gain Equations

The Raman propagation equations for one pump and one signal interacting, and by neglecting the double Raleigh backscattering, amplified spontaneous emission and thermal noise, are given by [6]

$$\frac{dp_p}{dz} = \pm\left(\frac{\upsilon_p}{\upsilon_s}\frac{g_R}{A_{eff}\Gamma}p_p p_s + \alpha_p p_p\right) \qquad 1$$

$$\frac{dp_s}{dz} = \frac{g_R}{A_{eff}\Gamma}p_p p_s - \alpha_s p_s \qquad 2$$

where + and – denote, respectively, the forward and backward propagation waves, p_p and p_s are, respectively, the pump and signal power. α, A_{eff}, g_R and Γ are fiber losses, effective area of optical fiber, Raman gain coefficient, and polarization factor between the pump and signal light, respectively. From the upove two coupled Raman amplifier equations, the signal power of an amplifier of length L is

$$p_s(L) = p_s(0)\exp\left(g_R p_0 L_{eff}/A_{eff} - \alpha_s L\right) \qquad 3$$

where p_0 is the input pump power, L is the fiber length, and L_{eff} is the effective fiber length which can be defined as

$$L_{eff} = \left[1 - \exp\left(-\alpha_p L\right)\right]/\alpha_p \qquad 4$$

The effective Raman gain $G_{R(eff)}$ is defined as

$$G_{R(eff)} = \frac{p_s(L)}{P_s(0)} \qquad 5$$

Subsituting eq.(3) into eq.(5) gives

$$G_{R(eff)} = G_R \exp(-\alpha_s L) \qquad 6$$

where G_R is the Raman gain, given by

$$G_R = \exp\frac{g_R p_0 L_{eff}}{A_{eff}} \qquad 7$$

Equation (6) takes into account the contributions of both Raman gain and fiber losses.

For high fiber losses $(L\alpha_p >> 1)$, $G_R \approx \exp\frac{g_R p_0}{A_{eff}\alpha_p}$, since $L_{eff} \cong 1/\alpha_p$.

In decibels (dB), $G_{R(eff)dB} = 10\log G_{R(eff)}$

$$G_{R(eff)dB} = 10\left(\frac{g_R p_0 L_{eff}}{A_{eff}} - \alpha_s L\right)\log(e) \tag{8}$$

where e is the base of natural logarithm

$$G_{R(eff)dB} = 4.343\left(\frac{g_R p_0 L_{eff}}{A_{eff}} - \alpha_s L\right) \tag{9}$$

Note that when the pump is off, the amplifier gain becomes

$$G_{R(off)} = \exp(-\alpha_s L) \tag{10}$$

When the pump is on, then the amplifier gain is given by eq.(6), (i.e. $G_{R(on)} = G_R \exp(-\alpha_s L)$), therefore, the ratio between the two cases (pump on to pump off cases) is given by G_R.

2. 2 Effective Area Of Fibers

The effective area A_{eff} of the fiber is a quantity of a great importance for Raman amplification and it is defined as [7]

$$A_{eff} = \frac{\iint_S |E_p(x,y)|^2 dxdy \iint_S |E_s(x,y)|^2 dxdy}{\iint_S |E_p(x,y)|^2 |E_s(x,y)|^2 dxdy} \tag{11}$$

where $E_{p,s}$ is the electric field of the pump and signal, respectively, and S denotes the fiber cross section in term of intensity

$$A_{eff} = \frac{\iint_S I_p(x,y)dxdy \iint_S I_s(x,y)dxdy}{\iint_S I_p(x,y) I_s(x,y)dxdy} \tag{12}$$

where $I_{p,s}$ is the pump, signal intensities, respectively. Equation (12) shows that A_{eff} accounts for the overlap between the fields of pump and signal over fiber cross section. Hence, A_{eff} provides more complete information on Raman properties of the fibers.

In analysis Raman amplifiers, it is worth to introduce Raman gain efficiency γ_R which can be defined as [8]

$$\gamma_R = \frac{\iint_S g_R(x,y) I_p(x,y) I_s(x,y)dxdy}{\iint_S I_p(x,y)dxdy \iint_S I_s(x,y)dxdy} \tag{13}$$

where g_R is the Raman gain coefficient. If g_R is assumed to be independent on x and y, and by using the definition in eq.(12), γ_R can be expressed as

$$\gamma_R = \frac{g_R}{A_{eff}} \tag{14}$$

The effective area of standard single-mode fiber (SMF) is around 80 μm^2. Dispersion-shifted fiber (DSF) is usually characterized by an effective area in the range (50-55) μm^2, while the effective area in dispersion-compensation fiber (DCF) is around 35 μm^2. The effective area of PCF varies strongly with structure parameters. An effective area as low as 1.5 μm^2 has been reported for PCF [1]. Manipulating the air hole diameter d and hole pitch Λ of the PCFs makes it possible to change effective index of the cladding and thus the field distribution in the fiber, as a consequence, the A_{eff} and γ_R can be modified.

Because of the changeable values of A_{eff} in PCFs, many approximated methods have been proposed to evaluate it, such as, $A_{eff} \approx \Lambda^2$ or depending on the effective radius r_{eff}, assuming $r_{eff} \approx \frac{\Lambda}{2}$, $\Lambda - \frac{d}{2}$ and so on [7]. In this paper, A_{eff} is calculated using the following expression for r_{eff}.

$$r_{eff} = \Lambda - \sum_{n=1}^{N} k_n d^n \tag{15}$$

where $k_1, k_2, \ldots\ldots k_N$ are fitting parameters extracted from published experimental or numerical simulated data.

The effective area of PCF can be approximated as

$$A_{eff} = \pi\left(\Lambda - \sum_{n=1}^{N} k_n d^n\right)^2 \qquad (16)$$

Investigating eq.(16) leds to important fact that, A_{eff} can be minimize by suitable choosing the optimum values of Λ and d . To find these values, let

$$c_n = k_n\left(\frac{d}{\Lambda}\right)^n \qquad (17)$$

The effective radius of the fiber in term of c_n will be

$$r_{eff} = \Lambda - \sum_{n=1}^{N} c_n \Lambda^n \qquad (18)$$

In this work, the fitting parameters $k_1, k_2, \ldots\ldots k_N$ in eq.(15) are estimated for triangular PCFs using the data reported in Ref. [7]. The authors in this reference have used a detailed numerical model to assess the dependence of A_{eff} and confinement loss on various structure parameters of triangular PCFs. The estimated fitting parameters are listed in Table 1.

3. Results And Disscussion

Raman amplification in different fiber types are considered in order to get guide lines to design PCFs with enhance Raman amplification compared with other fibers. In the following analysis, a fixed separation near to $\Delta\upsilon = 13.2THz$ between pump and signal is assumed, for maximum Raman gain efficiency. The signal and pump wavelengths are 1550 nm and 1450 nm , respectively.

3. 1. Raman Amplification in Different Fiber Types

The signal carrying information are Raman amplified during its transmission in fibers. Figures 3 (a and b) show, respectively, the characteristics of Raman amplification in different fibers for forward pump power P_p of 0.3 W, and 0.9 W. Four types of fibers are considered here: Standard silica single-mode fiber (SMF), dispersion-shifted fiber (DSF), dispersion- compensation fiber (DCF), and photonic crystal fiber (PCF). The Raman gain coefficient g_R is 0.334×10^{-16} km/W for PCFs and 0.796×10^{-16} km/W for others. Then, the Raman gain efficiency $\gamma_R = g_R / A_{eff}$ for these fibers will be :- $9.95 \times 10^{-7}\ (Wkm)^{-1}$, $1.59 \times 10^{-6}\ (Wkm)^{-1}$, $2.27 \times 10^{-6}\ (Wkm)^{-1}$, and $2.23 \times 10^{-5}\ (Wkm)^{-1}$, respectively.

Note that the PCF offers the highest signal level among the fibers. This result is obtained since the PCF has the largest Raman gain efficiency, γ_R , among these fibers. Note also that there is an optimum value of fiber length, L_{opt} , which yields maximum signal level (i.e., optimum Raman gain G_{opt}). Table 2 summarizes the values of L_{opt} and G_{opt} for different fiber types as estimated from Figs. 3. Investigating Table 2 reveals the following fact. The PCF offers the highest Raman gain among fibers which is achieved using shortest fiber length

Table 1. Estimated fitting parameters for triangular PCFs.

Λ	k_1	k_2	k_3	k_4	k_5	k_6
7.750	2.365	-3.377	1.277	-0.205	0.012	—
3.875	-3.850	11.784	-14.703	8.238	-2.145	0.212
2.583	-0.036	1.082	-4.686	4.684	-1.893	0.276
1.938	22.836	-70.703	79.048	-38.798	7.058	—
1.550	-3.735	17.520	-30.648	21.941	-5.589	—
1.200	-1.394	6.393	-9.955	4.507	—	—

Table 2. Optimum parameters of forward Raman amplification.

Fiber type	Optimum gain G_{opt} (dB)			Optimum length L_{opt} (km)		
	$P_p = 0.3$ (W)	$P_p = 0.6$ (W)	$P_p = 0.9$ (W)	$P_p = 0.3$ (W)	$P_p = 0.6$ (W)	$P_p = 0.9$ (W)
SMF	3.515	11.682	20.431	18.206	30.938	35.025
DSF	8.252	21.812	30.843	26.126	35.125	27.199
DCF	14.071	29.039	34.490	32.414	26.164	16.640
PCF	33.430	36.938	38.870	4.045	2.146	1.501

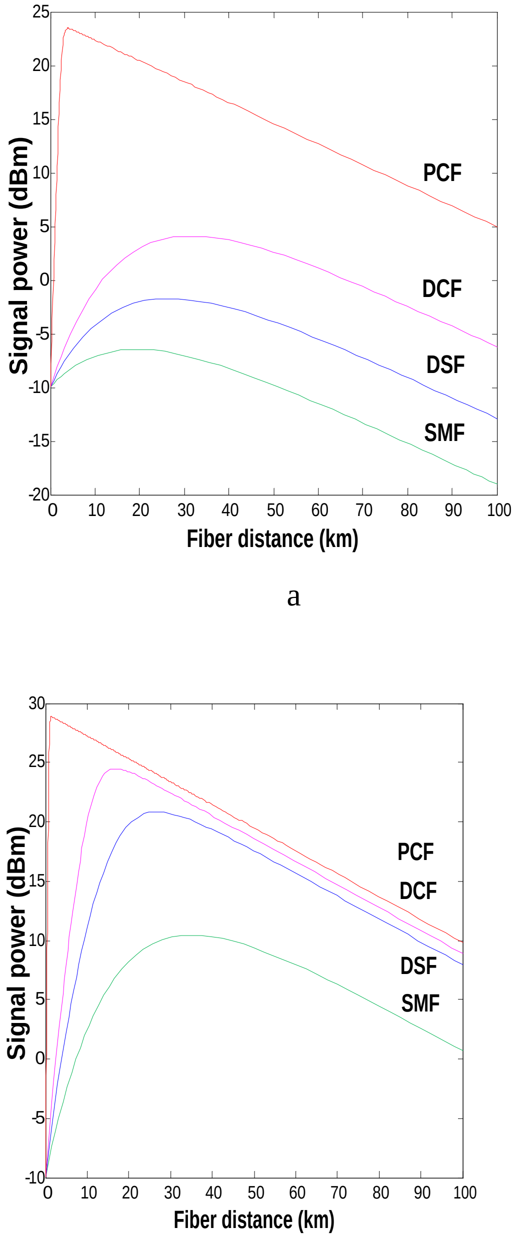
3. 2. Comparison Between SMF and PCF

This subsection gives a deep sight in comparison between SMF and PCF regarding to forward pumping. Different parameters are used in comparison; optimum gain G_{opt} and its corresponding optimum fiber length L_{opt}, and the maximum allowable fiber distance at which the input signal power returns to its starting value Z_{used}.

Figure 4 shows the signal power distribution along the fiber for 1 W pump power in forward scheme. Figures 5 (a-c) show, respectively, the variation of L_{opt}, G_{opt} and Z_{used} with pump power. Investigating Figs. 4 and 5 reveals that the PCF offers minimum values of L_{opt}, maximum values of G_{opt} compared with SMF. Not also that PCF offers the maximum allowable values of Z_{used} compared with SMF. This feature arises from the ability of PCF to transmit signals with a large value of gain. Table 3 summarizes the values of L_{opt}, G_{opt}, and Z_{used} with different P_p for both PCF and SMF. Thus, a conclusion arises, in long distance communications, it is better to exchange the SMF by PCF to transmit signals along the fiber.

3.3 Raman Amplification in PCF

The comparison given in previous subsection highlights the advantages of using PCF over SMF. This section focuses on the variation of PCF-based Raman amplifier characteristics with effective area and fiber loss. Figures 6 shows the variation of G_{opt} with A_{eff} of PCF for P_p = 300 mW, and 900 mW. The results are presented for different values of α, 0.25 dB/km, 0.5 dB/km, 0.75dB/km and 1 dB/km.. Figures 7 shows the dependence of Z_{used} on α for three different values of A_{eff}, 1.5 μm^2, 3.5 μm^2 and 5.5 μm^2. Investigation of Figs. 6 and 7 reveasl the following findings: Both effective area and fiber loss play important roles in determining Raman amplification. Both G_{opt} and Z_{used} decrease with increasing effective area and fiber loss



a

b

Figs. 3. Evaluation of signal power for different fiber types using forward pump power.

a- P_p = 0.3 W, b- P_p = 0.9 W

The parameter Z_{used} is almost independent on pump power and this effect is more prounced when P_p is high.

Table 4 lists the expected values of G_{opt} for different values of A_{eff} and P_p. In these calculation, the PCF is assumed to be fabricated with fiber loss of 0.25 dB/km at λ = 1.55 μm. This is equivalent to the loss of conventional SMFs operating at this wavelength. Note that G_{opt} higher than 33.405 dB can be obtained even for 300 mW pump power when A_{eff} is 1.5 μm^2

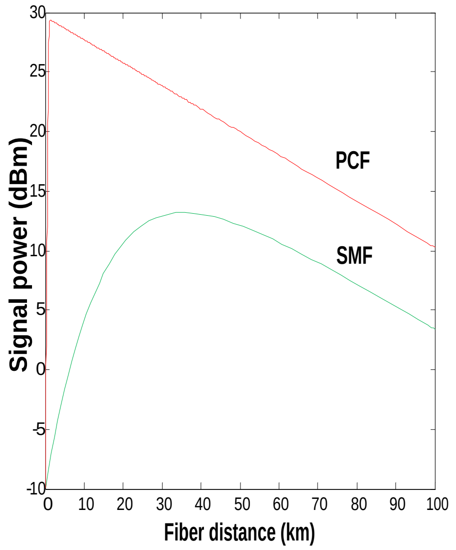
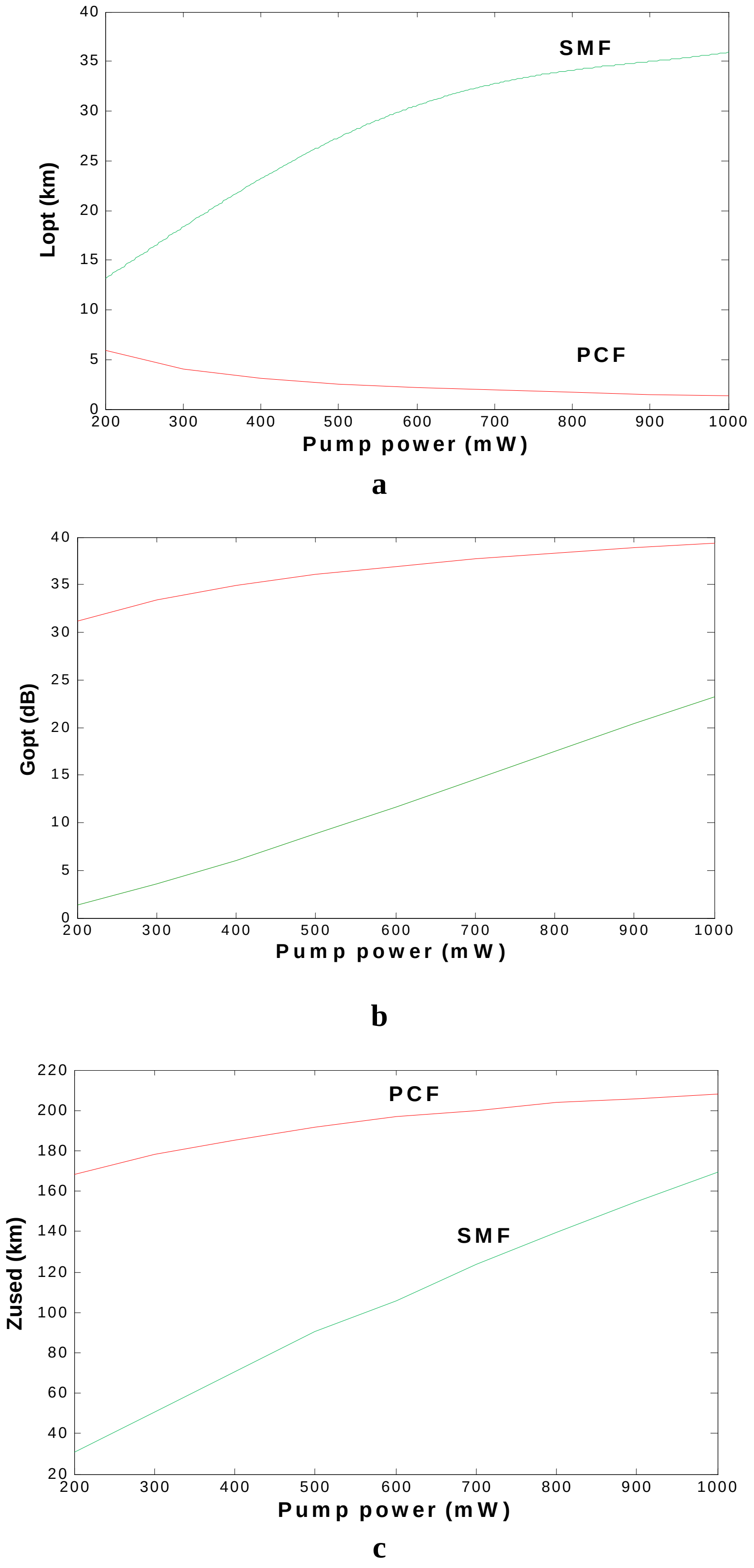


Fig. 4. Evaluation of signal power using P_p = 1 W

Table 3. Comparison between SMF and PCF using different affecting parameters.

Pump power (mW)	Optimum length L_{opt} (km)		Optimum gain G_{opt} (dB)		Used fiber length Z_{used} (km)	
	SMF	PCF	SMF	PCF	SMF	PCF
200	13.206	5.884	1.326	31.174	30.706	168.280
300	18.206	4.045	3.515	33.431	50.706	178.130
400	22.913	3.118	6.075	34.928	70.413	185.450
500	27.814	2.548	8.826	36.046	90.314	191.610
600	30.938	2.132	11.682	36.939	105.764	197.080
700	31.709	1.901	14.605	37.681	123.899	200.000
800	34.688	1.668	17.541	38.316	139.783	203.700
900	35.025	1.499	20.431	38.871	154.739	205.550
1000	35.868	1.367	23.194	39.363	169.450	207.860

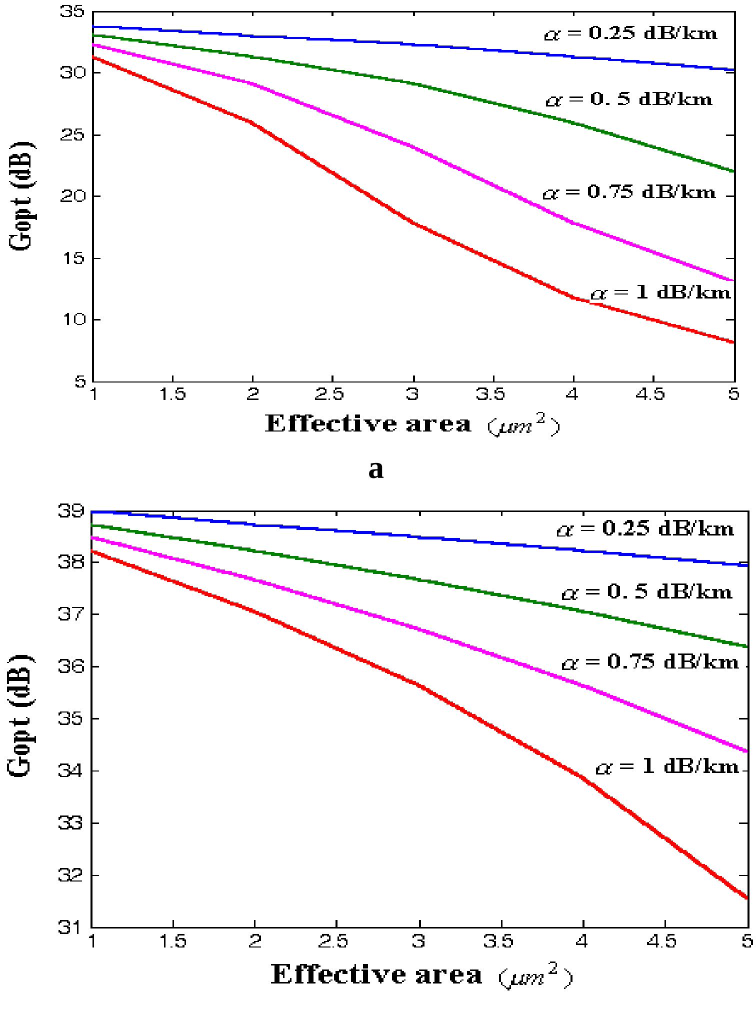


Figs. 5. Comparison between SMF and PCF.

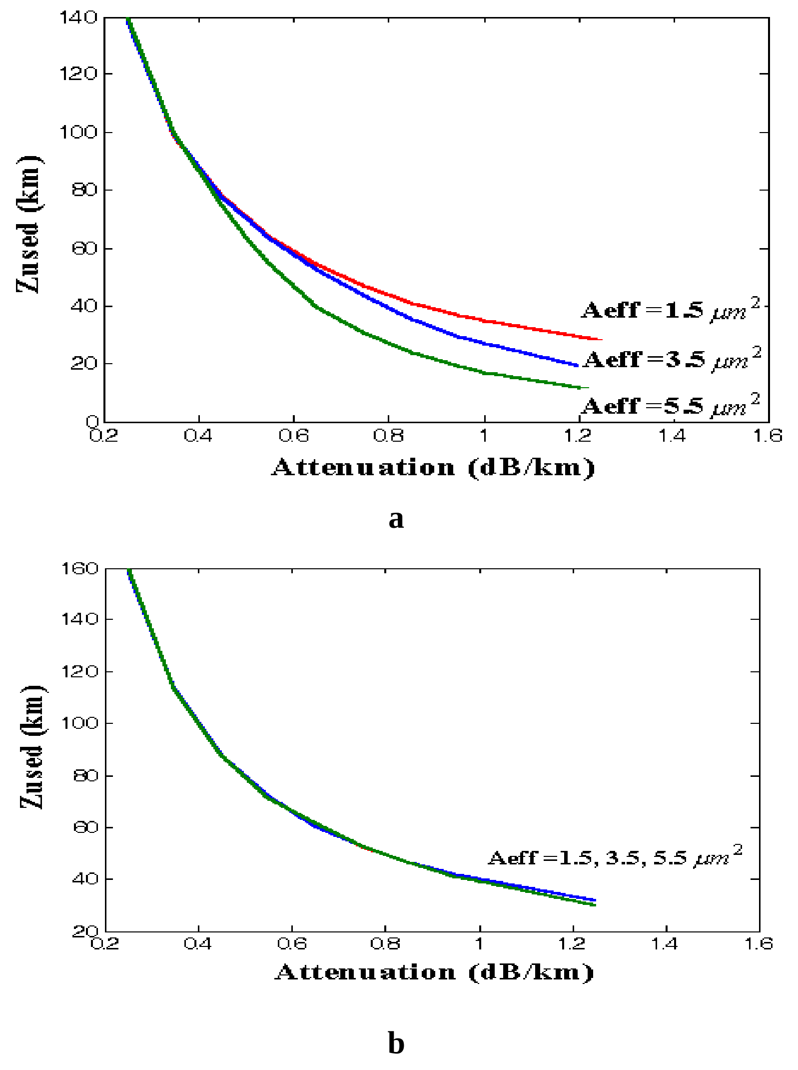
a- The variation of L_{opt} with P_p, **b-** The variation of G_{opt} with P_p, **c-** The variation of Z_{used} with P_p.

Table 4. G_{opt} in PCF-based Raman amplifier

P_p (mW)	G_{opt} (dB)		
	A_{eff} = 1.5 (μm^2)	A_{eff} = 3.5 (μm^2)	A_{eff} = 5.5 (μm^2)
300	33.405	31.778	29.676
600	36.924	36.149	35.292
900	38.859	38.341	37.792



Figs. 6. Variation of optimum gain with effective area for different values of PCF attenuation.
a- P_p = 0.3 W, b- P_p = 0.9 W.



Figs. 7. Dependence of Z_{used} on PCF attenuation for different values of PCF effective area.
a- P_p = 0.3 W, **b-** P_p = 0.9 W.

Conclusions

A comprehensive investigation of Raman amplification in photonic crystal fibers (PCFs) has been reported. The results have been compared with those related to conventional Raman amplifiers. The main conclusions drawn from this study are

i- The PCF offers the highest Raman gain which is achieved using shortest fiber length. At 900 mW forward pumping, an optimum gain of 20.4 dB, 30.8 dB, 34.5 dB and 38.9 dB is obtained using 35 km-SMF, 27.2 km-DSF, 16.6 km-DCF, and 1.5 km-PCF fabricated with 1.5 μm^2 effective areas, respectively.

ii- The parameter Z_{used} is almost independent of pump power P_p and this effect is more pronounced when P_p is high.

iii- Raman gain higher than 33 dB can be obtained in 1.5 μm^2 PCF even for 300 mW forward pump power.

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تحليل ومحاكاة مضخم رامان في الفايبر البصري البلوري

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الخلاصة

في هذا البحث تم البحث بالتفصيل عن خصائص مضخم رامان المصنوع من الفايبر البصري البلوري مع مقارنة ادائه مع مضخمات رامان المصنوعة من الفايبرات الاعتيادية. افادت الدراسة انه يمكن استخدام نتائج المحاكاة التي وثقت هنا لتصميم PCF-FRAs ذات مواصفات تفوق مثيلاتها المصنوعة من الفايبر الاعتيادي، كذلك يمكن الحصول على ربح قدره (33dB) عند قدرة ضخ صغيرة (300 mW) اذا صُمم الفايبر بشكل جيد.