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一种增益平坦的光子晶体拉曼光纤放大器

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摘　要：为解决传统拉曼放大器增益系数低和增益不平坦的问题，采用级联光子晶体光纤的设计方法设计了一种增益平坦的拉曼光纤放大器．采用受激拉曼散射效应的稳态分析理论，分析了光子晶体光纤的拉曼增益谱，建立了拉曼放大器的理论模型．通过解耦合方程，推导了实现增益平坦的约束条件，发现光纤长度和泵浦功率是影响拉曼光纤放大器增益平坦度的两个参数．仿真结果表明，在 1 508～1 544 nm 的带宽范围内，实现了一个增益高达 21 dB，增益平坦度仅为 0.14 dB 的光子晶体拉曼光纤放大器，可在光纤通信系统应用中发挥重要作用．

关键词：拉曼放大器；光子晶体光纤；高非线性；增益平坦度；级联光纤
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Gain-flattened Photonic Crystal Raman Fiber Amplifier

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Abstract: A gain-flattened Raman fiber amplifier was proposed by using the method of cascading photonic crystal fiber, which improves the Raman gain coefficient and reduces the gain flatness of the traditional Raman fiber amplifier. Based on steady-state analysis theory of the stimulated Raman scattering effect, the photonic crystal fiber Raman gain spectrum and established the theoretical model of this Raman amplifier were analyzed. Through solving the coupled equation, the constraint condition for realizing gain-flattened is deduced, showing that the fiber length and pump power are two parameters affecting gain flatness of Raman fiber amplifier. Numerical simulation results show that a photonic crystal Raman fiber amplifier with 21 dB high gain and only 0.14 dB gain flatness over the bandwidth range of 1 508 nm to 1 544 nm, can be obtained. It will play an important role in the design of high efficient optical fiber communication systems.

Key words: Raman amplifier; Photonic crystal fiber; High nonlinear; Gain flatness; Cascading optical fiber
OCIS Codes: 230.4480; 060.2320; 060.2330; 060.2310

0 Introduction

With the rapid development of modern information technology, the role of Raman Fiber Amplifier (RFA) in communication system becomes more and more important in recent years[1]. It can directly amplify the attenuated signal in optical domain, and greatly enhances the network controlling and

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processing capacities[2-3], so it is a key device in the all-optical network. Compared with other optical fiber amplifiers, it has many distinct advantages, such as high gain, fast response speed, wide gain broadband, good noise performance, and realizing amplification of arbitrary band, thus, it has been widely researched in optical communication system[4-6].

Meanwhile, a new type of fiber, calledPhotonic Crystal Fiber (PCF)[7], has been used as Raman gain medium[8-9]. Since 1996, Knight, *et al.* reported the first PCF[10], the development of PCF undoubtedly received extensive attention of people. Theoretical and experimental studies have recently been performed on PCF, which demonstrate that PCF has a series of significant features like low loss, easy controllable dispersion and high nonlinear effects[11], all these show that PCF has potential application for high gain Raman amplifier. Furthermore, Gong, *et al.* reported cascaded fiber method for designing gain-flattened RFA[12-13], which overcomes the disadvantages of RFA using multi-pumping schemes[11], such as the high cost, complicated structure and so on. Nowadays, Photonic Crystal Raman Fiber Amplifier (PC-RFA) is still at the primary stage of development, and comprehensive analysis and study is developing gradually[10].

In this paper, we use thecascading PCFs design method and only two pumps to achieve gain-flattened RFA. The theoretical model of this Raman amplifier is established by combining the calculation of Raman coefficient and the solution of the coupled equation. Two pieces of fiber correspond to different frequency-shifts in PCF′s Raman gain spectrum, the first is for amplification, and the second is for compensation. By numerical simulation, we achieved a high gain and low gain flatness PC-RFA. It is essential for the super-long distance transmission, super-wide bandwidth and super-fast speed optical communication system.

1 Theoretical modelof RFA

1.1 Mathematical model

In the N-channel Wavelength-Division Multiplexing (WDM) system, the forward steady-state coupled equation of RFA based on stimulated Raman scattering is as follows[14]

$$\begin{cases} \dfrac{\mathrm{d}n_i(z)}{\mathrm{d}z} = -\alpha_i n_i(z) + \sum\limits_{j=1}^{N} r_{ij} n_j(z) n_i(z) \\ n_i(z)\big|_{z=0} = n_i(0) \qquad i = 1,2,\cdots,N \end{cases} \tag{1}$$

where $n_i(z)$ denotes the i-th channel photon flux at z, α_i is the i-th channel attenuation coefficient, r_{ij} is the Raman gain efficiency of photon flux between Channel i and Channel j, and $r_{ij} = g_{ij}/A_e$[15], where g_{ij} is the power Raman gain coefficient between channel i and channel j, The analytical solution of the coupled equation is expressed in the form of power as follows[14]

$$\begin{cases} P_i = P_i(0)\exp(-\alpha_i z)\dfrac{P_\Sigma(0)}{\sum\limits_{j=1}^{N} \dfrac{\bar{\nu}}{\nu_j} P_j(0)\mathrm{e}^{G_{ji}}} \qquad i = 1,2,\cdots,N \\ P_i(0) = n_i(0)h\nu_i \\ P_\Sigma(0) = \sum\limits_{j=1}^{N} P_j(0)\dfrac{\bar{\nu}}{\nu_j} \\ G_{ji} = -\dfrac{k}{\bar{\lambda} M A_e}(\tilde{\nu}_j - \tilde{\nu}_i)\cdot P_\Sigma(0)\cdot L_e \end{cases} \tag{2}$$

where P_i is the i-th channel optical light power, $\tilde{\nu}_i$ is the i-th channel wavelength number ($\tilde{\nu}_i = 1/\lambda_i$), whose unit is cm^{-1}, G_{ji} is the Raman gain between i-th and j-th channel, $\bar{\lambda}$ denotes the average value of all channel wavelength, ν_i is the pump light frequency, k is the slope of the least square fitting line, M is the polarization-maintaining coefficient, A_e is the effective cross-sectional area. L_e is the effective interaction length, which can be expressed by the actual interaction length as $L_e = [1 - \exp(-\alpha L)/\alpha]$, and is only related with the attenuation coefficient α, L is the fiber length.

In Eq. (2), we only consider the interaction of pump light and signal light, ignoring the SRS effect between signal lights. Meanwhile, we assume that the first channel $j=1$ is for the pump light and the rest of the N-1 channels are for the signal lights, and they enter into the optical fiber together, then Eq. (2) can be simplified to

$$P_i(z) = P_i(0)\exp(-\alpha_i z)\exp\left[\frac{g_{pi}}{\lambda_p MA_{\mathrm{e}}}\cdot P_1(0)\cdot L_{\mathrm{e}}\right] \tag{3}$$

When two pieces of optical fiber are cascaded, the signal light power at the end of the first optical fiber is

$$P_i(L_1) = P_i(0)\exp(-\alpha_i L_1)\exp\left[\frac{g_{1pi}}{R_1 MA_{\mathrm{e}}}\cdot P_{p1}(0)\cdot L_{\mathrm{e}\ 1}\right] \tag{4}$$

Regarding the output signal light power of the first optical fiber L_1 as the input light power of the second optical fiber L_2, the output light power at the end of the second optical fiber L_2 can be calculated as

$$P_i(L_1+L_2) = P_i(0)\exp\left[-\alpha_i(L_1+L_2)+\frac{g_{1pi}}{R_1 MA_{\mathrm{e}}}\cdot P_{p1}(0)\cdot L_{\mathrm{e}1}+\frac{g_{2pi}}{R_2 MA_{\mathrm{e}}}\cdot P_{p2}(0)\cdot L_{\mathrm{e}2}\right] \tag{5}$$

where R_i can be defined as $R_i=\frac{\lambda_{ip}}{1.45}(i=1,2)$, $g_{1pi}(\Delta\nu)$ and $g_{2pi}(\Delta\nu)$ denote the Raman gain coefficient of the first and the second optical fiber, respectively. In order to achieve the high gain RFA, the selected gain medium must have high nonlinear coefficient. The PCF is a potential candidate, and its Raman gain coefficient is much higher than ordinary fiber. Fig . 1 shows the Raman gain spectrum of PCF when the pump wavelength is 1 450 nm[16], which has a broad gain range and high Raman gain coefficient. By observing carefully, the linear characteristic of Raman gain spectrum is fairly evident over the [8, 12.6] THz ([267, 420] cm^{-1}) and [14,16] THz ([467, 533] cm^{-1}) frequency-shift range. Moreover, the variation trend of these two sections are exactly adverse, in which the first section is an increasing function of g_R, while the second section is reversed, so cascading and fitting a straight line with them, Raman gain spectrum flattening can be achieved.

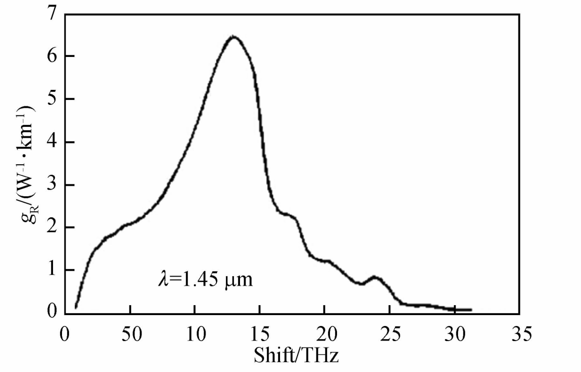

Fig. 1 Raman gain spectrum of photonic crystal fiber

Here, $g_{1pi}(\Delta\nu)$ and $g_{2pi}(\Delta\nu)$ are both linear, so they can be expressed as follows

$$\begin{cases} g_{1pi}(\Delta\nu) = k_1(\nu_{p1}-\nu_i)+b_1 \\ g_{2p}(\Delta\nu) = k_2(\nu_{p2}-\nu_i)+b_2 \end{cases} \tag{6}$$

where k_1, k_2, b_1, b_2 is the slope and intercept of least squares fitting line, respectively. In order to express conveniently, we define Q is

$$Q = \frac{g_{1pi}}{R_1 MA_{\mathrm{e}}}\cdot P_{p1}(0)\cdot L_{\mathrm{e}1}+\frac{g_{2pi}}{R_2 MA_{\mathrm{e}}}\cdot P_{p2}(0)\cdot L_{\mathrm{e}_2} \tag{7}$$

By combining Eqs. (6) and (7), one can obtain

$$\begin{aligned} Q = \frac{1}{MA_{\mathrm{e}}}\Big[&\frac{k_1\nu_{p1}+b_1}{R_1}\cdot P_{p1}(0)\cdot L_{\mathrm{e}1}+\frac{k_2\nu_{p2}+b_2}{R_2}\cdot P_{p2}(0)\cdot L_{\mathrm{e}2}- \\ &\nu_i\frac{k_1}{R_1}\cdot P_{p1}(0)\cdot L_{\mathrm{e}1}+\frac{k_2}{R_2}\cdot P_{p2}(0)\cdot L_{\mathrm{e}2}\Big] \end{aligned} \tag{8}$$

If Q is larger than the optical fiber loss value, and it is unrelated with the signal light frequency, gain-flattened RFA can be realized. Thus, if the coefficients of the items containing the signal light frequency equals to zero, the constraint condition of achieving gain-flattening can be obtained

$$\frac{k_1 P_{p1}(0)L_{\mathrm{e}1}}{\lambda_{p1}}+\frac{k_2 P_{P2}(0)L_{\mathrm{e}2}}{\lambda_{p2}} = 0 \tag{9}$$

As one can see from the above equation, the optical fiber length and pump power are two main factors affecting the gain flatness of RFA. As a consequence, if one of the factors is controlled, the influence on gain flatness of RFA from the other factor can be analyzed.

1.2 The structure design of photonic crystal Raman fiber amplifier

In Fig. 2, we displayed the structure diagram of a cascaded PC-RFA. Its amplification principle is the stimulated Raman scattering effect in optical fiber. When the strong pump light and weak signal light are injected into the first optical fiber together through the combiner, due to the stimulated Raman scattering effect, the pump light will transfer part of its energy to the signal lights. As a result, the signal lights are amplified on the different degrees. Then the pump light is filtered by the filter at the end of the first optical fiber. Next, the second pump light and signal lights are injected into the second optical fiber, in a manner similar to the above process, the signal lights are compensated by the effect of pump light. Finally, the signal lights are output through the separator. What′s more, they are almost amplified on the same degree, consequently, the low gain flatness is achieved.

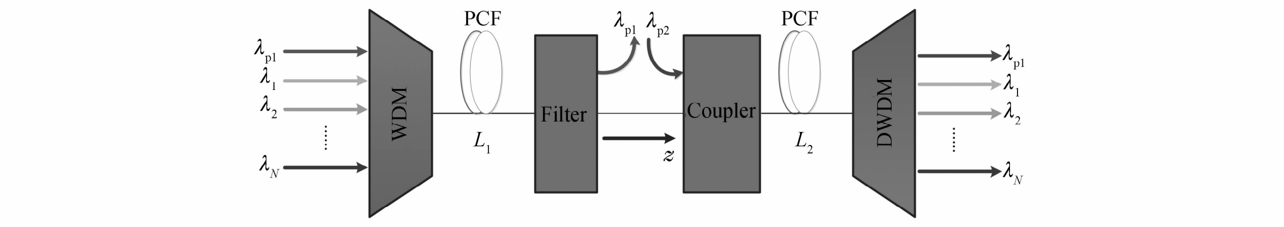

Fig. 2 Structure diagram of photonic crystal Raman fiberamplifier

2 Simulation results and analysis

2.1 Gain and gain-flatness simulation results of PC-RFA

The designed PC-RFA is consisted of two parts. The first part is for amplification, and the second is for compensation. In the first fiber, the pump wavelength λ_{p1} and power P_{p1} are 1450 nm and 0.9 W respectively, the frequency-shift range of the first pump light and all the signal lights is [8, 12.6] THz, the parameters of linear fitting gain spectrum are: $k_1 = 0.65 \times 10^{-15}$ m • cm/W, $b_1 = -0.8398 \times 10^{-13}$ m/W. Then, according to the frequency-shift formula, the signal light wavelength range can be calculated as [1508, 1544] nm, and the channel spacing is 1 nm, initial input signal light power is 0.01 mW. In the second optical fiber, the frequency- shift range of the second pump light and all the signal lights is [14, 16] THz, the parameters of linear fitting gain spectrum are: $k_2 = -1.57 \times 10^{-15}$ m • cm/W, $b_2 = 9.164 \times 10^{-13}$ m/W. The pump wavelength λ_{p2} is 1 410.2 nm. Here, we assume the first and the second optical fiber length is the same, they are both 0.2 km. According to Eq. (9), pump power P_{p2} can be calculated as 0.36 W. In the Matlab simulation process, the other system parameters are set as follows: the effective cross-sectional area of PCF is 3 μm^2, the polarization-maintaining coefficient M is 2. There are different attenuation coefficients for different light wavelengths, and their values can be obtained through the attenuation spectrum of PCF. The simulation results are as Figs. 3 and 4.

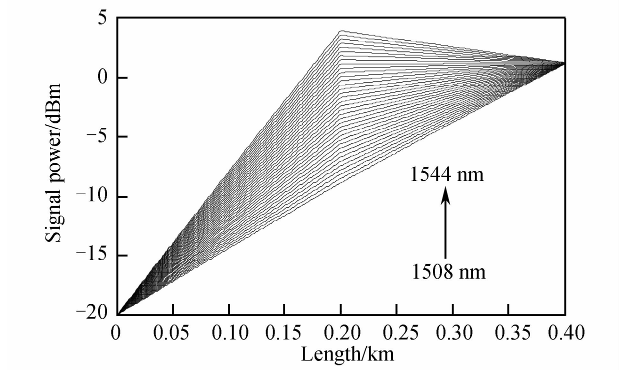

Fig. 3 The varying curve of signal power changing with the fiber length

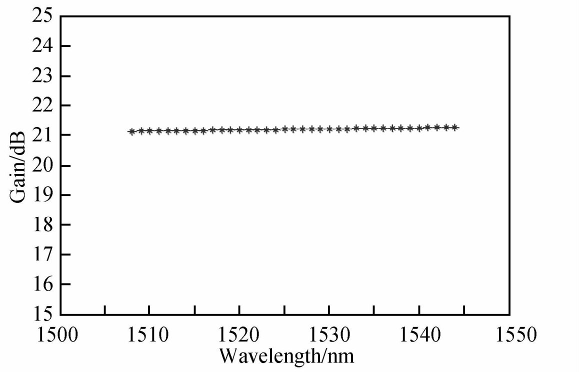

Fig. 4 The gains of PC-RFA

The simulation results show that the gain of PC-RFA designed by this method reaches up to 21.25 dB, and the gain flatness is only 0.14 dB. As we can see from Fig. 3, in the first optical fiber, because of the effect of the first pump light λ_{p1}, the signal light powers of the different wavelength are enhanced. In other words, the signal lights are amplified. However, because the Raman gain spectrum of the frequency-shift range [8, 12.6] THz is increased gradually, the amplified extent of each signal light is different. The signal light power of long wavelength is higher than the short wavelength. In the second optical fiber, when the second pump light λ_{p2} is injected, signal lights are compensated, and the output signal powers are almost the same when the fiber length is 0.4 km, the reason is that Raman gain spectrum of the chosen frequency-shift rang [14, 16] THz is decreased gradually and its trend is exactly opposite with the first gain spectrum trend. Thus, through two pieces of optical fiber transmission, optical powers converge gradually, and the gain flatness is reduced.

The optical fiber length and pump power are two important factors affecting the gain flatness of RFA. When arbitrary one factor between them is changed, the gain and gain flatness will change with it. Here, we analyze two optical fiber lengths are the same with above, and the pump powers are increased, if $P_{p1}=1.2$ W, the P_{p2} can be calculated as 0.5 W. Through the simulation, the gain of the designed PC-RFA has reached to 28.58 dB, but the gain flatness has deteriorated to 0.52 dB. Its gain change is shown in the Fig. 5.

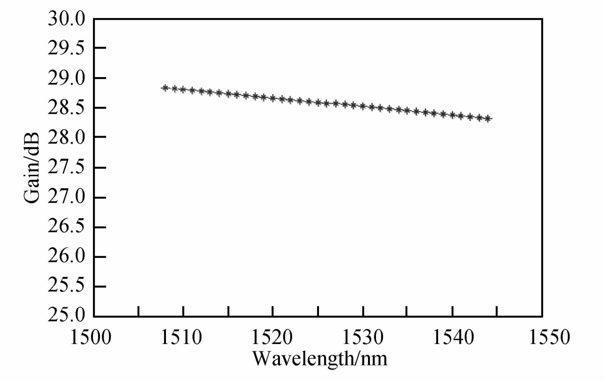

Fig. 5 The gains of PC-RFA

2.2 The influence of parameters on the gain of RFA

2.2.1 *The influence of optical fiber length on the gain of RFA*

In order to study the influence of optical fiber length on the gain of RFA, we designed a simple WDM system, for which is that a pump light and arbitrary three different wavelength signal lights are injected into the optical fiber through the combiner together, and the PCF corresponding to frequency-shift range [8, 12.6] is chosen as the gain medium. In the transmission fiber, based on the Raman amplification principle, the gain changes with optical fiber length can be analyzed. The system parameters are set as follows: the optical fiber length is 10 km, pump power and wavelength are 0.03 W and 1 450 nm, signal light wavelengths are 1 508 nm, 1 520 nm and 1 530 nm and other system parameters are the same as those in Sec. 2.1. Through numerical simulation, the following result can be gotten:

It is evident in Fig. 6 that the signal light gain of different wavelength in the designed RFA increases firstly and then decreases with the fiber length, and every signal light has its gain maximum. Meanwhile, the gain of long wavelength is larger than short wavelength, this result exactly accords with the Fig. 3. And the fiber length is longer when the longer wavelength signal light reaches its gain maximum. Thus, in the design process, if we need the appropriate gain of RFA, the fiber length can be changed properly according the result.

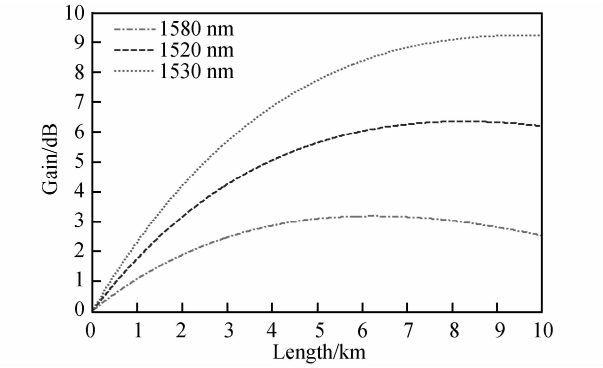

Fig. 6 Signal light gain changing with the fiber length

2.2.2 *The influence of pump power on the gain of RFA*

In order to study the gain change of signal light with pump power, we also can design the other system, for which is that a pump light and a signal light are injected into the optical fiber together. What is different with above is that the changing range of pump power should be given firstly. Through numerical simulation, the gain change of signal light with pump power can be analyzed. The system parameters are set as follows: the pump wavelength is 1 450 nm, the pump power changes between 0.5 W and 1 W, the wavelength and initial power of signal light are 1 508 nm and 0.01 mW respectively, the optical fiber length is 0.5 km, and other system parameters are the same as those in

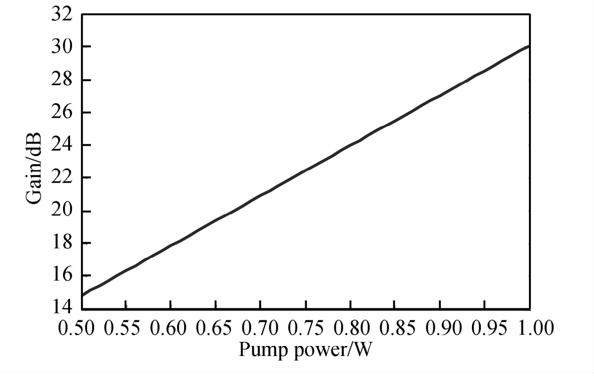

Fig. 7 Signal light gain changing with the pump power

Section 2.1. What can be seen from Fig. 7 is that the signal light gain can still be improved with the increasing pump power, and the growth trend is almost linear.

3 Conclusions

PCF is a new kind of optical fiber, it has high Raman gain efficiency and strong nonlinear effect. So it is usually used to develop high gain RFA. In this paper, a gain-flattened PC-RFA is theoretically designed and numerically demonstrated. Because of using only two pumps and shorter fiber, its structure is simple, and the cost is lower. What's more, its gain value is very high, which is about 21 dB, and the gain flatness is very low. When the pump power is further increased, the PC-RFA's gain increases, but the gain flatness deteriorates. Then the influence of optical fiber length and pump power on the gain of RFA is analyzed, all these prove the feasibility of this designed RFA.

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