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Double-pump cascade tellurite-based Raman fiber amplifier based on polynomial fitting of gain spectrum

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Abstract: Bandwidth, gain and gain-flattening of Raman fiber amplifier (RFA) directly impact on the transmission quality of fiber communication system. RFA with two-pump cascade tellurite fiber was put forward that it will aim for optimizing these parameters according to the features of tellurite fiber Raman gain spectrum (RGS). And the constraints of fiber lengths and pumping parameters were derived when achieving gain-flattening. Quintic polynomial fitting on RGS can accurately reflect the information of RGS and simplify the conditions of achieving gain-flattening. Through Matlab simulation verification, when the two fibers are respectively 0.339 km and 0.16 km, the peak gain is 17.81 dB, gain-flattening is 0.66 dB, and amplified bandwidth is 48 nm. This project supplies a new approach for designing RFA with wide bandwidth, high gain and low gain-flattening.

Key words: Raman fiber amplifier (RFA), tellurite-based Fiber, optical fiber cascade, gain flatness, polynomial fitting of gain spectrum
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基于增益谱多项式拟合的双泵浦碲基光纤级联拉曼光纤放大器

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摘要:光纤拉曼放大器的带宽、增益及增益平坦度直接影响了光纤通信系统的传输质量.针对这些参数的优化,根据碲基光纤的拉曼增益谱特性提出了一种双泵浦级联碲基光纤的拉曼放大器结构.并推导了实现增益谱平坦时光纤长度和泵浦参数满足的约束条件.经过对拉曼增益谱的 5 次多项式拟合,更准确地反映了拉曼增益谱的信息,同时也简化了其实现增益谱平坦的条件.通过 Matlab 仿真分析得到,当两段光纤分别取 0.339 km,0.16 km 时,其最大增益为 17.81 dB,增益平坦度为 0.66 dB ,放大带宽为 48 nm.该方案为宽带宽、高增益、增益平坦度小的拉曼光纤放大器设计提供了一种新的思路.

关　键　词:拉曼光纤放大器;碲基光纤;光纤级联;增益平坦;增益谱多项式拟合

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Introduction

Dense Wavelength Division Multiplexing (DWDM) is more and more focused on all-optical network due to high capacity and low cost. However, the transmission distance of optical signal[1] is limited by the self-loss of single-mode silica fiber and the chaining loss of optical fiber communication system. Erbium Doped Fiber Amplifier (EDFA) solves the problem of long haul transmission. However, with the increasing communication capacity, DWDM system needs a high demand of optical

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amplifier. Since the operation range of EDFA is only in L-band[2-3], it is urgent to design a new optical amplifier with wide bandwidth, high gain and low gain-flattening. Compared with EDFA, RFA has plenty of advantages, such as swift response time, high saturated output power, easy couple and realizing the amplification of arbitrary waveband[4-5] *et al.*, which is widely applied in optical communication transmission system. RFA broadens the amplified bandwidth of EDFA in 400G/1T ultra-high speed and super-long distance of optical fiber communication transmission system, which effectively improves the transmission capacity of DWDM system.

Generally speaking, Raman gains coefficient (RGC)[6-7] of pure silica fiber is too low. In order to acquire higher gains, RFA needs pumping source with higher power and longer silica fiber[8]. Hence, it is important to design a new optical fiber material with high RGC and wide gain spectrum. Tellurite fiber is one material of inorganic non-oxide glass. Compared with pure silica fiber, tellurite fiber not only has a higher RGC, but also possesses a broader range of RGS[9-10], and it is extremely stable in chemical property and temperature property. By polynomial fitting on tellurite fiber RGS, this paper used tellurite fiber cascaded two pieces as a model and adopted a method of compensating after amplifying to achieve a wide bandwidth, high gain and low gain-flattening RFA.

1 Theoretical foundation and design principle

1.1 Theoretical model

Stimulated Raman scattering, which is widely applied in many fields, is a nonlinear optical effect. It converts projectile high-frequency photon into low-frequency photon by the energy conversion between photon and molecule, which achieves amplification of signal optical power[11]. The study of RFA used fiber as medium has already made great progress[12-13]. Coupled equation of pumping light and signal light in fiber is:

$$\begin{cases} \dfrac{\partial P_i}{\partial z} = \dfrac{g_{ip}}{MAe_N} P_p P_i - \alpha_{Ni} P_i \\ \dfrac{\partial P_p}{\partial z} = -\dfrac{\omega_p}{\omega_i} \dfrac{g_{ip}}{MAe_N} P_p P_i - \alpha_{Np} P_p \end{cases} , \quad (1)$$

where P_p, P_i are the pumping light power and the signal light power, α_{Np}、α_{Ni} are the loss coefficient of the pumping light and the i^{th} signal light in n^{th} fiber, ω_i、ω_p are the lightwave frequencies of the pumping light and the signal light, M, is the polarization-maintaining coefficient. When pumping light polarization and signal light polarization are identical, M = 1. When the two lightwave polarizations are arbitrary, M = 2[14]. Ae_N is the effective area of n^{th} fiber. g_{ip} is the normalized RGC and it can be calculated by $r_{pi} = g_{ip}/Ae$[15].

In small signal model, pumping light power far outweighs signal light power($P_p \gg P_i$) and the influence of signal light on pumping light is negligible. Hence, the pumping light is approximately calculated as following:

$$P_p(z) = P_p(0)e^{-\alpha_p z} \quad . \quad (2)$$

By cascading different fibers, output powers of all signal lights in second fiber can be calculated[16] as following:

$$P_i(L_1 + L_2) = P_i(0)\exp\left(-\alpha_{i1}L_1 - \alpha_{i2}L_2 + \frac{g_{ip1}}{MAe_1}P_{p1}(0)Le_1 + \frac{g_{ip2}}{MAe_2}P_{p2}(0)Le_2\right) , \quad (3)$$

where $P_i(L_1 + L_2)$ is the output optical power of second fiber, L_1、L_2 are the lengths of the first fiber and the second fiber, Le_1、Le_2 are effective interaction lengths of the first fiber and the second fiber, and the Le can be shown as: $Le = (1-e^{-\alpha L})/\alpha$, $P_i(0)$ is the initial optical powers of all signal lights, α_{i1}、α_{i2} are the signal light loss coefficients of the first fiber and the second fiber, g_{ip1}`、$g_{ip2}$` are the Raman gain coefficients of the first fiber and the second fiber under the pump of the first pumping light λ_{p1} and the second pumping light λ_{p2}. $P_{p1}(0)$、$P_{p2}(0)$ are initial pumping optical powers of the first pumping light λ_{p1} and the second pumping light λ_{p2}.

Assuming:

$$-\alpha_{i1}L_1 - \alpha_{i2}L_2 + \frac{g_{ip_1}}{MAe_1}P_{p1}(0)Le_1 + \frac{g_{ip_2}}{MAe_2}P_{p2}(0)Le_2 = Q \quad . \quad (4)$$

In Eqs. 3 and 4, in order to bring about firm output of all signal light powers, Eq. 4 satisfies $Q > 0$. Q-value is effectively converged when the parameters of all signal lights are specific values. There are differences between loss coefficient and normalized RGC of the distinct signal lights transmitted in fiber. For achieving firm output of all signal light powers, it is necessary to consider using g_{ip2}` to compensate $g_{ip1}$`.

According to gain formula $G = 10\log(P_{out}/P_{in})$, P_{out} is the amplified optical power and P_{in} is the unamplified signal light power, the final gain of signal light is expressed as following:

$$G = 10\log\exp(-\alpha_{i1}L_1 - \alpha_{i2}L_2 + \frac{g_{ip_1}}{MAe_1}P_{p1}(0)Le_1 + \frac{g_{ip_2}}{MAe_2}P_{p2}(0)Le_2) \quad . \quad (5)$$

1.2 The analysis of tellurite fiber and its RGS

In discrete RFA, the optical fiber is short. Therefore, it is necessary to choose appropriate fiber as the gain medium. Compared with silica fiber, special optical fiber has a higher RGC, such as tellurite and chalcogenide fiber etc. Tellurite fiber has a higher RGC and it is extremely stable with chemical property and temperature property.

Figure 1 shows the tellurite fiber RGS when pumping light wavelength λ_0 is 1.460 μm. By observing, RGS has a broad gain range. In frequency-shift range of [0, 800] cm^{-1}, pumping light has an amplification effect on signal light. When frequency-shift range of pumping light and signal light are [570, 650] cm^{-1} and [740, 820] cm^{-1} respectively, RGS has a well linearity. At the left and right of the second wave crest, RGC firstly increases and then decreases with the increasing of wavelength, which shows a good linearity. Hence, it is a way to superpose the two parts of Raman gains by pumping different pumping lights, which could achieve the Raman gain-flattening, namely adopting the method of compensating after amplifying. Without doubt, the gains are

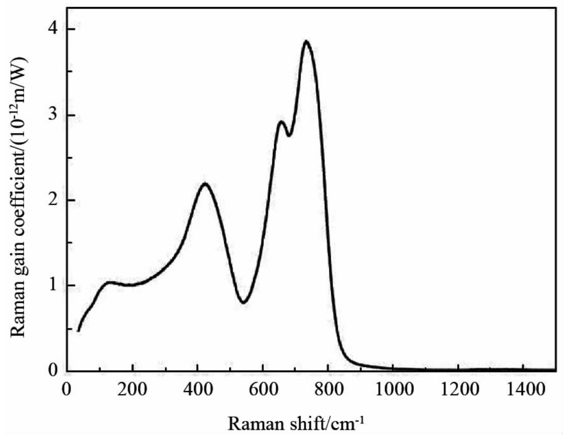

Fig. 1 Tellurite fiber RGS
图1 碲基光纤的拉曼增益谱

compensated after being amplified by using the features of crest and trough in Fig. 1, which can realize the gain-flattening.

1.3 The structure design of tellurite RFA

Figure 2 is the tellurite RFA structure diagram, which adopts a method of compensating after amplifying. λ_{p1} is the wavelength of the first pumping light, λ_{p2} is the wavelength of the second pumping light, λ_1-λ_{48} are the wavelengths of 48 signal lights, which continue to increase. L_1 and L_2 are the lengths of the first and second tellurite fiber. To start with, pumping light λ_{p1} and signal light enter into the first tellurite fiber through the combiner. By SRS effect, signal lights are amplified in different degrees. They enter into the filter in the tail of the first tellurite fiber and filter pumping light λ_{p1}. Next, implanting the second pumping light λ_{p2} and the signal lights into the second tellurite fiber through the combiner, the signal lights receive gain compensation under the action of pumping light λ_{p2}. Finally, signal light powers of all wavelengths achieve nearly equal amplification times by the output of the filter. And then, the conditions of achieving gain-flattening will be calculated.

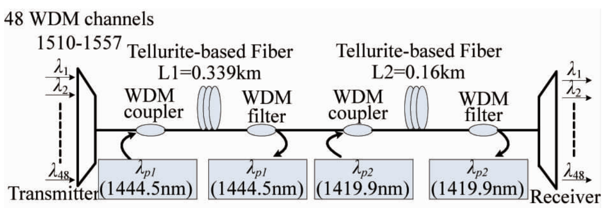

Fig. 2 Tellurite RFA Principle Diagram
图2 碲基RFA的原理图

In Eq. 5, $g_{ip1}(\Delta v)$, $g_{ip2}(\Delta v)$ are the RGC of the first and the second tellurite fiber. When $g_{ip1}(\Delta v)$, $g_{ip2}(\Delta v)$ are nonlinear in a certain frequency-shift range, they are obtained that:

$$g_{ip1}(\Delta v) = a_1\Delta v^n + b_1\Delta v^{n-1} + c_1\Delta v^{n-2} + \cdots\cdots \quad n\to\infty \quad , \quad (6)$$

$$g_{ip2}(\Delta v) = a_2\Delta v^n + b_2\Delta v^{n-1} + c_2\Delta v^{n-2} + \cdots\cdots \quad n\to\infty \quad , \quad (7)$$

In Eqs. 6 and 7, $a_1, b_1, c_1\cdots$. and $a_2, b_2, c_2\cdots$. are all coefficients of two fitted curves. In order to facilitate discussion, assuming $n=2$, the following two equations can be gotten.

$$g_{ip1}(\Delta v) = a_1\Delta v^2 + b_1\Delta v + c_1 \quad , \quad (8)$$

$$g_{ip2}(\Delta v) = a_2\Delta v^2 + b_2\Delta v + c_2 \quad , \quad (9)$$

$a_1, b_1, c_1\cdots$ and $a_2, b_2, c_2\cdots$ are all coefficients of two conic equations. Known:

$$g_{ip1}(\Delta v) = \frac{\lambda_0}{\lambda_{p1}} g_{ip1}(\Delta v) \quad , \quad (10)$$

$$g_{ip2}(\Delta v) = \frac{\lambda_0}{\lambda_{p2}} g_{ip2}(\Delta v) \quad . \quad (11)$$

Assume:

$$W = \frac{g_{ip1}}{MAe} P_{p1}(0) Le_1 + \frac{g_{ip2}}{MAe} P_{p2}(0) Le_2 \quad . \quad (12)$$

If W-value is more than the loss value of optical fiber and unrelated to signal light frequency, it can materialize gain-flattening. It can be determined as follows by solving the Eqs. 8 ~ 12 simultaneously.

$$W = \frac{1}{MAe}\left[\begin{array}{l} \frac{\lambda_0}{\lambda_{p1}}(a_1 v_{p1}^2 + b_1 v_{p1} + c_1) p_{p1}(0) Le_1 + \frac{\lambda_0}{\lambda_{p2}}(a_2 v_{p2}^2 + b_2 v_{p2} + c_2) p_{p2}(0) Le_2 \\ + v_i\left[\frac{\lambda_0}{\lambda_{p1}}(-2a_1 v_{p1} - b_1) p_{p1}(0) Le_1 + \frac{\lambda_0}{\lambda_{p2}}(-2a_2 v_{p2} - b_2) p_{p2}(0) Le_2\right] \\ + v_i^2\left[\frac{\lambda_0}{\lambda_{p1}} a_1 p_{p1}(0) Le_1 + \frac{\lambda_0}{\lambda_{p2}} a_2 p_{p2}(0) Le_2\right] \end{array}\right] \quad . \quad (13)$$

Assuming the polynomial coefficient with signal light frequency is zero, it can be concluded as following:

$$\begin{cases} \frac{\lambda_0}{\lambda_{p1}} a_1 p_{p1}(0) Le_1 + \frac{\lambda_0}{\lambda_{p2}} a_2 p_{p2}(0) Le_2 = 0 \\ \frac{\lambda_0}{\lambda_{p1}}(-2a_1 v_{p1} - b_1) p_{p1}(0) Le_1 + \frac{\lambda_0}{\lambda_{p2}}(-2a_2 v_{p2} - b_2) p_{p2}(0) Le_2 = 0 \end{cases} \quad . \quad (14)$$

Equation 14 is the constraint which can achieve the gain-flattening by quadratic polynomial fitting on RGS. M, Ae, v_{p1}, v_{p2}, λ_0, λ_{p1}, λ_{p2}, a_1, b_1, c_1 and a_2, b_2, c_2 are the determined values as the bandwidth of amplified signal light and RGS are confirmed. Accordingly, gain-flattening is only related to the two pumping light powers and two fiber lengths. Likewise, the constrain, which can achieve the gain-flattening by n^{th} degree polynomial fitting on RGS, can be obtained. As a consequence, RFA gain-flattening is only related to two pumping light powers and two fiber lengths when the bandwidth of amplified signal light and RGS are confirmed.

2 The analysis of simulation results and influence factors

2.1 The simulation and analysis of polynomial fitting tellurite RFA

A rule can be received by observing the tellurite fiber GRS: when frequency shifts of pumping light and signal light are in the range of [300, 500] cm^{-1}, the linetype of tellurite fiber RGS presents "convex peak", while the linetype presents "valley" when they are in the range of [420,620] cm^{-1}. Utilizing this rule, GRS flatness can be achieved by superposing the "convex peak" and the "valley" and pumping with the different wavelengths pumping lights. When the wavelength range of signal light is [1510, 1575] nm, the pumping light wavelength of the amplified part in the frequency shift ranges of [300,500] cm^{-1} λ_{p1} is 1 444.5 nm. Hence, the pumping light wavelength of the compensated part in the frequency-shift ranges of [420,620] cm^{-1} λ_{p2} is 1 419.9 nm. The principle construction diagram is shown in Fig. 2. The expressions of g_{ip1} and g_{ip2} can be obtained by the quintic polynomial fitting on RGS in the frequency shift ranges of [300,500] cm^{-1} and [420,620] cm^{-1}.

System parameters are as follows: the wavelength of the first pumping light λ_{p1} is 1 444.5 nm, power P_{p1} is 1 W. The wavelength range of signal light implanted into the fiber is [1510,1557] nm, channel spacing is 1 nm. There are 48 signal lights with different wavelengths. The injection power of signal light is 0.01 mW. The wavelength of the second pumping light λ_{p2} is 1419.9nm, power P_{p2} is 1.05 W. As the two optical fibers use tellurite fiber, the effective area of fibers Ae_N is 22.1 μm^2. Polarization coefficient M is 2, the attenuation coefficient of pumping light in the first fiber α_{p1} is 24 dB/km, and the attenuation coefficient of pumping light in the second fiber α_{p2} is 26 dB/km. Tellurite fiber's length of amplified part L_1 is 0.339 km. According to Eq. 14, what can be calculated is that the fiber length of the compensated part L_2 is 0.16 km. Figure 3 is the regular diagram of the optical power of 48-channel signal lights changing with the fiber length. Figure 4 is the gains of all signal lights.

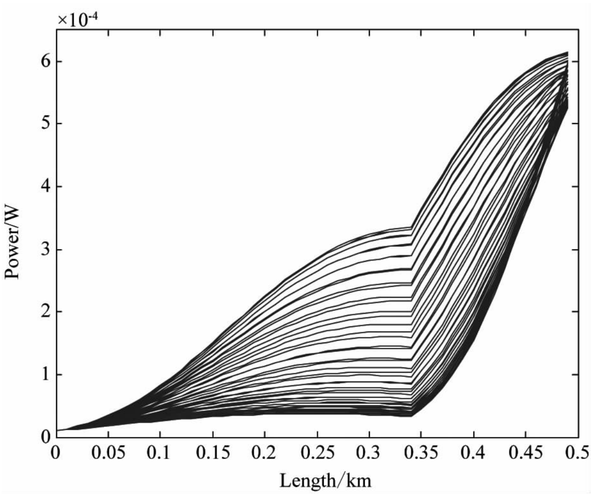

Fig. 3 The varying curve of signal light power changing with the fiber length
图 3 信号光功率随光纤长度的变化曲线

According to Fig. 3, signal light power is amplified firstly and then compensated. When optical fiber length is at 0 ~ 0.339 km, the differences of frequency shift between all signal lights and pumping lights lead to the differences of signal lights gains and their power differences gradually increase. When optical fiber length is at

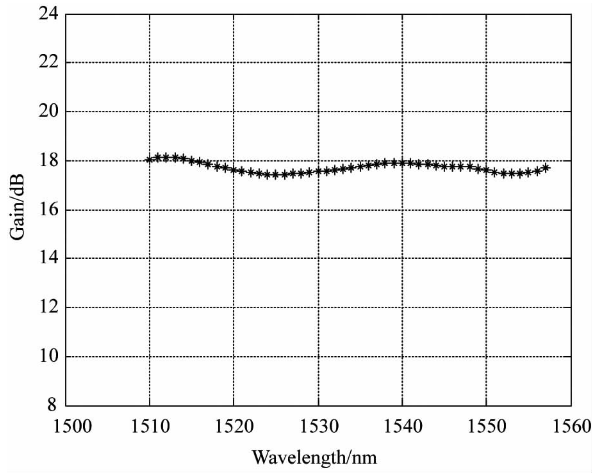

Fig. 4 the gains of all signal lights
图 4 各个信号光的增益

0.339 ~ 0.499 km, the differences of signal lights power gradually decrease, and the gain-flattening reaches the minimum when the fiber length is at 0.499 km. Consequently, the average gain of signal light in the bandwidth range of 48 nm is 17.81dB, the gain-flattening is only 0.66dB. Figure 4 shows the gains of all signal lights amplified by RFA. There are some reasons of gain-unflattening. Firstly, RGC of superposing the tellurite fiber RGS in [300, 500] cm^{-1} and [420, 620] cm^{-1} is not a fixed value and exists some fluctuations. Secondly, the attenuations of signal lights with different wavelengths in tellurite fiber are also different, and the calculation error will bring about the gain-unflattening. Besides, signal light gain and gain-flattening are affected by pumping light power. When other parameters remain unchanged, setting pumping power P_{p1} = 1.1 W, P_{p2} = 1.2 W, 21.02 dB average gain has been obtained and gain-flattening has deteriorated 1.01 dB. Hence, with the increasing of pumping light power, the gain of signal light increases while gain-flattening deteriorates.

The method mentioned above, which is polynomial fitting on tellurite fiber RGS, has been adopted. RFA bandwidth reaches 48 nm, and gain-flattening is 0.66 dB. If the pumping power increased, gain-flattening will deteriorate gradually. In the process of practical application, wide bandwidth, high gain and low gain-flattening RFA which can be got from polynomial fitting will be better used in the DWDM system. Tellurite RFA only needs a few hundred meters of fiber, while silica fiber needs a few kilometers for achieving the same gain. It not only saves the material but also cuts down the cost and maintains easily.

2.2 The influence of parameters on RFA

2.2.1 The influence of fiber length

System is designed that one pumping light and much signal lights are implanted into one tellurite fiber simultaneously and studies the signal light power changing with the transmission distance. System parameters are as follows: The wavelength of pumping light is 1 440.2 nm, power is 0.9 W. The wavelength range of the amplified signal light is [1540, 1559] nm, channel spacing is 1 nm, a total of 20 signal lights are input, their power is

0.01 mW. The other parameters in this system are in accordance with the parameters in polynomial fitting RFA. Fiber length is 0.5 km. Simulation result is shown as Fig. 5. Figure 5 shows that signal light power increases and then decreases with the increasing of fiber length and the power at 1 559 nm wavelength signal light reaches the maximum when the fiber length is at 0.35 km. When the fiber length is less than 0.35 km, the Raman gain of signal light outweighs its loss, therefore, the signal light power is increasing. However, when the fiber length is more than 0.35 km, the differences between Raman gain quantity and the loss part are decreasing gradually with the increasing of fiber length, so signal light power tends to gradually decline.

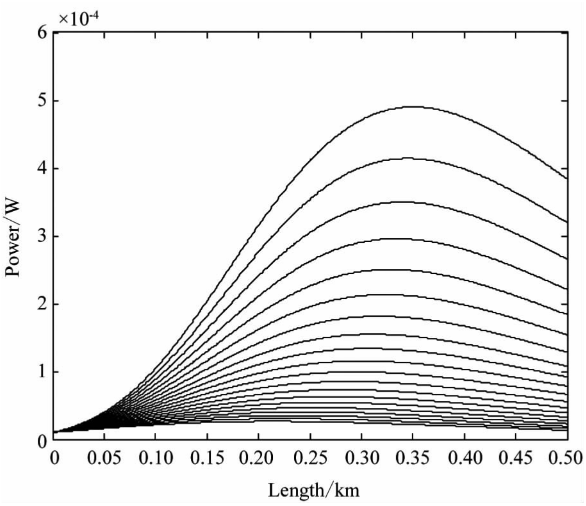

Fig. 5 signal light power changing with the fiber length
图 5 信号光功率随光纤长度的变化

Figure 6 shows the rule of the gains obtained by different wavelength signal lights changing with the fiber length. Apparently, the signal gain increases and then decreases with the increasing of fiber length, which is identical with power changing rule. When fiber length is a fixed value, the longer wavelength signal light achieves larger gain. The fiber lengths are diverse when all signal lights reach the peak gains. When the short wavelength signal light preferentially attains, the corresponding fiber length increases with the increasing of wavelength in sequence.

2.2.2 The influence of pumping light power

Designing a new system is one pumping light and single signal light are implanted into one tellurite fiber simultaneously to study the rule of signal light gain changing with the pumping power. Parameters are set as following: pumping light wavelength is 1 440.2 nm, signal light wavelength is 1559 nm, the input power of signal light is 0.01 mW, and the changing range of pumping light power is 0.8 ~ 1.5 mW. Tellurite fiber length is 0.3 km. The other parameters in this system are in accordance with the parameters in polynomial fitting RFA. Figure 7 shows the gain and the pumping light power show a positive correlation, which is almost a linear growth.

3 Conclusions

It's an effective method of using fiber cascade to a-

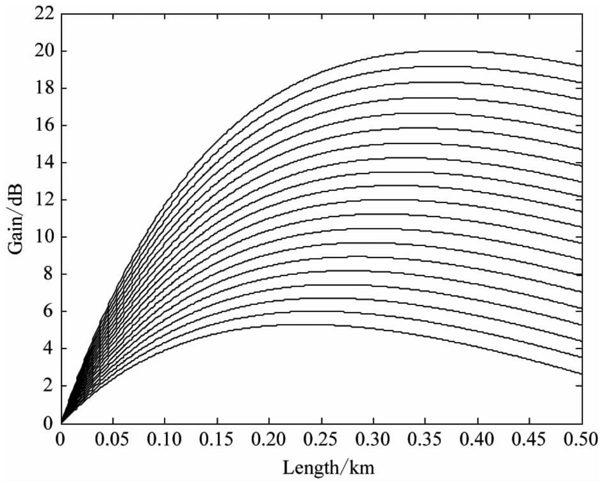

Fig. 6 Signal light gain changing with the fiber length
图 6 信号光增益随光纤长度的变化

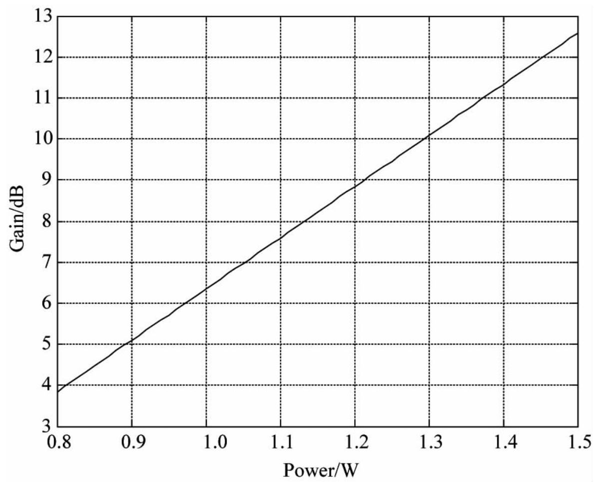

Fig. 7 Signal light gain changing with the pumping power
图 7 信号光增益随泵浦功率的变化

chieve gain-flattening. This paper presents the analysis theory of fiber cascade to achieve gain-flattening and analyzes the gain-flattening conditions in the case of polynomial fitting on RGS. Taking Raman amplifier of cascading two-segment tellurite fiber as the example can calculate the optimal gain value obtained by signal light. When the first fiber is 0.339 km and the second fiber is 0.16 km, the RFA with 17.81 dB peak gain, 0.66 dB gain-flattening and 48 nm bandwidth are obtained through Matlab simulation verification, which proves the feasibility of analysis theory.

The advantages of this project are simple in entire structure, using polynomial fitting on RGS to get a larger amplified bandwidth and having a well gain and gain-flattening. Compared with straight line fitting, curve fitting can reflect the information of gain spectrum more accurately. Hence, its simulation result will be more precise. The theory of RFA proposed by this paper is suited to two random cascaded fibers with the gain-complementarity property for constructing gain-flattening RFA. Consequently, it has been a major research goal to design and manufacture novel optical fibers which made of various materials and produce cascade fiber amplifiers with the gain-complementarity features above.

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