Optics Communications 423 (2018) 6–11

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Numerical modeling and optimization of cladding-pumped tapered fiber Raman amplifiers

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ARTICLE INFO

Keywords:
Raman fiber amplifiers
Cladding-pumping
Tapered fiber
Power scaling

ABSTRACT

We have theoretically investigated the amplification process in the cladding-pumped tapered Raman fiber amplifiers (RFAs) for the first time. The numerical results show the high order Stokes threshold and output power can be both significantly improved in the tapered Raman fiber (TRF) in comparison with conventional double-clad Raman fiber. The threshold of 2nd Stokes and the RFA output power could reach 3000 W and 2570 W when the fiber parameters are chosen according to the simulation results and manufacturing feasibility.

1. Introduction

Thanks to the wavelength independence, Raman fiber laser (RFL) sources have been rapidly developed in recent years as a supplement to rare-earth doped fiber lasers [1]. Core-pumped RFL is the most common architecture that has seen rapid progress recently. In 2009, Y. Feng et al. reported a more than 150 W spectrally-clean continuous wave Raman fiber laser at 1120 nm with an optical efficiency of 85% [2]. In 2013, H.W. Zhang et al. demonstrated a high-power high-efficiency single-mode all-fiber RFL operating at 1173 nm and obtained output power of 119 W at a wavelength of 1173 nm [3]. However, compared with pump brightness, the output brightness of these core-pumped RFLs actually has decreased. In that case, the upper limit of output power for the core-pumped RFLs is determined by the development of nearly diffraction-limited YDFLs. To enhance the brightness, several methods have been proposed, such as using graded-index fibers and cladding pumping.

In 2016, Y. Glick et al. reported a 978 nm, 154 W continuous-wave diode-pumped Raman fiber laser based on graded-index fiber whose brightness enhancement could reach up to 8.4 [4]. In 2017, S.A. Barbin et al. demonstrated an all-fiber configuration based on conventional multimode graded-index passive fiber directly pumped by fiber-coupled commercial multimode laser diodes at 915 nm, the brightness enhancement factor is larger than 12 [5].

The cladding-pumping scheme which has improved the YDFLs at 1 μm waveband was first reported by H.M. Pask [6]. In 2006, C.A. Codemard et al. demonstrated the cladding-pumped RFL at 1660 nm achieving 10.2 W single-mode output [7]. The improved degree of brightness enhancement factor over the pump laser beam is about 18.3. Later on, the output power of cladding-pumped RFL operating at 1120 nm was further scaled to 100 W [8]. In 2017, Shamir et al. reported a pulsed cladding-pumped RFL with 250 W average power, while the brightness enhancement factor was 4 [9]. However, the generation of high-order Raman light restricts power scaling of the cladding-pumped RFLs, due to the relatively large cladding-to-core area ratio. To suppress high-order Raman light, the double-clad Raman fiber (DCRF) has to be designed with sufficiently small cladding-to-core area ratio or large attenuation at longer wavelength, which limits the potential brightness improvement [10].

Tapered fiber is a special type of fiber whose core and cladding diameter vary with its longitudinal position. Due to its special geometric structure which leads to the increase of the nonlinear coefficient when the pump light is injected into the wide end, tapered fiber has been employed in supercontinuum generation [11]. And the improvement of the beam quality in rare-earth fiber lasers based on tapered fiber takes advantages of the decreasing radius [12,13]. The potentiality of power scalability of the tapered fiber when the pump light is injected into the narrow end has also been verified [14,15], and it could be attributed to its larger mode area, higher pump absorption and suppression to nonlinear effects. The experiment results in Ref. [15] shows that the tapered fiber could maintain the good beam quality as the small mode area (SMA) fiber. The output beam profile reveals a near diffraction limited beam quality. And the experiment results in Ref. [16] shows that the output laser operates in the fundamental mode with an almost Gaussian profile, even though the normalized frequency is about 6.4 in the output end, revealing that this pump scheme can maintain the generation of fundamental mode. In Ref. [17], C. Shi et al. have theoretically proved that tapered fiber could effectively maintain the

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https://doi.org/10.1016/j.optcom.2018.03.084
Received 17 January 2018; Received in revised form 13 March 2018; Accepted 31 March 2018

good beam quality if near fundamental mode field is injected from the small end.

However, cladding-pumped RFAs based on tapered fiber has never been reported so far. In this paper, we present a novel approach to raise the output power of cladding-pumped RFAs by using TRF. We demonstrated a theoretical model to describe geometric shape of TRF and power evolution of stimulated Raman scattering (SRS) in TRF and prove that the TRF can be applied to suppress high order Stokes in RFAs when the pump light is injected into the narrow end first. Next, the effects of the inner-cladding-to-core area ratio and the bump degree of tapered fiber on the RFAs performance were explored through simulation. The tapered fiber parameters were optimized to maximize the output power at different pump power levels. The simulation results show that the threshold of 2nd Stokes could vary about 3 times in DCRFs with and without tapered structure. Under 3000 W pump power, the output power reaches over 2570 W with slope efficiency of 86.2%. The theoretical study provides guidance on high-order Stokes suppression in cladding-pumped RFAs. In general, cladding-pumped RFAs based on TRF has the advantages of high 2nd Stokes threshold, high 1st Stokes output power and good beam quality maintenance. One could expect high power, high brightness RFAs utilizing TRF in future experiments.

2. Modeling of SRS in tapered fibers

Usually, the tapered fiber can be divided into three categories: linear tapered fiber, concave tapered fiber and convex tapered fiber. The diameter of small and big ends of the inner cladding are supposed to be D_1 and D_2 respectively. The inner-cladding-to-core area ratio remains constant along the longitudinal direction of the fiber. The total fiber length is L. The tapering ratio T is defined to be $T = D_2/D_1$, and average taper angle b_0 is defined to be $b_0 = (D_2 - D_1)/L$. For ordinary DCRF, the tapering ratio T is 1. The inner cladding radius $r_{clad}(z)$ variation along the longitudinal position z is given by [17]

$$r_{\text{clad}}(z) = \frac{b_0 - b}{2L} \cdot z^2 + \frac{b}{2} \cdot z + \frac{D_1}{2} \tag{1}$$

where b is the bump degree of the fiber that represents the parabolic shape factor which describes the longitudinal geometry of the fiber [17]. When b is in the range $0{\sim}2b_0$, r_{clad} increases monotonically with b. $0 < b < b_0$, $2b_0 > b > b_0$, and $b = b_0$ correspond to concave, convex and linear shapes, respectively. The inner cladding radius $r_{clad}(z)$ and the core radius $r_{core}(z)$ vary together along the fiber axis while the inner-cladding-to-core area ratio is constant. The three types of fiber are presented in Fig. 1(a)–(c).

In our simulation, only the pump light, 1st Stokes and 2nd Stokes are considered. Stokes higher than 2nd order is ignored. The 1st Stokes is considered as the signal light. The way we deal with the power distribution of different pump modes is just the same as Ref. [10]. We assume that the pump is distributed over the whole core and cladding region so that we can derive an "averaged" behavior. Here we take the same assumption as Ref. [10] that the pump and the Stokes distribution is a flat-top profile along the fiber length. Besides, this way of treating the pump mode distribution of cladding pumped RFAs even in multimode fiber has been quoted in many literatures such as Ref. [18]. With these approximations, the power evolution equations could be written as:

$$\begin{aligned}
\frac{\partial P_p(z)}{\partial z} &= -[\frac{P_1(z)}{A_{clad}(z)}\frac{\lambda_1}{\lambda_p} g_R(\lambda_p, \lambda_1) + a(z)]P_p(z) \\
\frac{\partial P_1(z)}{\partial z} &= [\frac{P_p(z)}{A_{clad}(z)} g_R(\lambda_p, \lambda_1) - \frac{\lambda_2}{\lambda_1}\frac{P_2(z)}{A_{core}(z)} g_R(\lambda_1, \lambda_2) - a(z)]P_1(z) \\
\frac{\partial P_2(z)}{\partial z} &= [\frac{P_1(z)}{A_{core}(z)} g_R(\lambda_1, \lambda_2) - a(z)]P_2(z) \\
A_{clad}(z) &= \pi \cdot r_{clad}^2(z) \\
A_{core}(z) &= \pi \cdot r_{core}^2(z)
\end{aligned} \tag{2}$$

In this equation, $P_p(z)$, $P_1(z)$, $P_2(z)$ denote the pump power, 1st Stokes power and 2nd Stokes power at the position z respectively. λ_P, λ_1, λ_2 denote the pump wavelength, 1st Stokes wavelength and 2nd Stokes wavelength respectively. $\alpha(z)$ denotes the transmission loss. $g_R(\lambda_P, \lambda_1)$ denotes the Raman gain coefficient from the pump to the 1st Stokes, while $g_R(\lambda_1, \lambda_2)$ denotes the Raman gain coefficient from the 1st Stokes to the 2nd Stokes. A_{clad} and A_{core} denote the cladding and core areas respectively.

The pump light $P_p(0)$ and the seed signal light $P_1(0)$ are injected into the inner cladding and the core of TRF separately. P_p would be converted into P_1 through SRS, leading to the amplification of P_1 through propagation. However, after $P_1(z)$ reaches the threshold, it will shift to $P_2(z)$. Thus, the output power would decrease. Except the 2nd Stokes, Other nonlinear optical effects may also have influence on the power scaling amplification for Raman fiber amplifiers, such as stimulated Brillouin scattering (SBS) and modal instability (MI).

SBS is nonnegligible in single-frequency or narrow band Raman fiber amplifiers. However, the object we discuss here is broad-band amplification. Therefore, SBS has very high threshold power so that it could be neglected. MI might be one of the factors that influences the power scaling of RFAs [19], which could cause the energy conversion between different modes and lead to the beam quality deterioration. MI could cause sharply dropping of the signal power when the higher order mode is not allowed and depleted. However, the core area increases with the axis position in tapered fiber, so does the allowed mode number. Even the signal power is beyond the MI threshold, the energy loss due to MI would hardly happen. Therefore, in the power amplification process, 2nd Stokes is the leading factor that influences the power promotion of RFAs if the beam quality deterioration is not considered.

From Eq. (2), the total gain of the 1st Stokes G_1^{SRS} and the 2nd Stokes G_2^{SRS} could be obtained as [10],

$$\begin{aligned}
G_1^{SRS} &= \frac{\lambda_1}{\lambda_p} g_R(\lambda_p, \lambda_1) \int_0^L \frac{P(z, \lambda_1)}{A_{clad}(z)} dz \\
G_2^{SRS} &= g_R(\lambda_1, \lambda_2) \int_0^L \frac{P(z, \lambda_1)}{A_{core}(z)} dz
\end{aligned} \tag{3}$$

Meanwhile, the 2nd Stokes introduced by noise would be amplified to be significant once the total gain is over 70 dB [10]. Hence, to suppress the 2nd Stokes, the power of the 1st Stokes must fulfill

$$\int_0^L \frac{P(z, \lambda_1)}{A_{core}(z)} dz \le \frac{70(\text{dB})}{g_R(\lambda_1, \lambda_2)} \tag{4}$$

For a normal DCRF, $A_{core}(z)$ is a constant along the axis, so Eq. (4) could be written as

$$\int_0^L P(z, \lambda_1) dz \le \frac{70(\text{dB})A_{core}}{g_R(\lambda_1, \lambda_2)} \tag{5}$$

While for a TRF in the case of small-end injection, $A_{core}(z)$ would increase monotonically along the longitudinal direction. According the mean value theorem, Eq. (5) could be rewritten as

$$\int_0^L P(z, \lambda_1) dz \le \frac{70(\text{dB})(A_{core} + \varepsilon)}{g_R(\lambda_1, \lambda_2)} \tag{6}$$

ε is an uncertain positive number. Comparing Eq. (5) with Eq. (6), the threshold power for 2nd Stokes in TRF could be higher than DCRF from qualitative analysis. This feature allows TRF has the potentiality to suppress high-order Stokes and improve the signal light power.

3. Results and discussions

In order to verify the accuracy of the model, we calculate the case of ordinary DCRF, using the same parameters as in [20]. The pump wavelength is 1550 nm. 1st and 2nd Stokes wavelength is 1660 nm and 1787 nm respectively. The core radius is 4.5 μm and the numerical aperture (NA) is 0.065. Raman gain coefficient is 0.634×10^{-13} m/W for the pump light, and the background loss is not considered corresponding to Ref. [20]. For a Raman amplifier, 1 kW pump light and 50 mW 1st Stokes is injected into one side, and the 2nd Stokes is introduced by noise at the beginning. The fiber length is carefully optimized for each