Impact of Input Pump Profile on the Gain Spectrum and the Saturation Behavior of One-Pump Fiber Optical Parametric Amplifiers

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ABSTRACT—In this article, the impact of input pump profile on the gain spectrum as well as the saturation behavior of one-pump fiber optical parametric amplifiers (FOPAs) is investigated. Since in practical circumstances, pump sources used for FOPAs have Lorentz-Gaussian profile instead of Gaussian, a more realistic case is considered for simulating FOPAs in this article. The results of simulations for the Gaussian and the Lorentz-Gaussian profiles show that a higher gain and a faster saturation are obtained for a pump with a Lorentz-Gaussian profile than a Gaussian pump. The results of this article provide a more realistic model for FOPAs.

KEYWORDS: gain spectrum, optical fiber, parametric amplification, pump profile, saturation.

I. INTRODUCTION

Fiber optical parametric amplifiers (FOPAs) working based on the four-wave mixing (FWM) in optical fibers have received great interest due to their widespread applications in various areas of science and technology [1], [2]. FOPAs can be used for high-gain amplification, wavelength conversion, signal processing, short pulse generation, noise suppression, etc. [3]-[10]. The underlying physics of a FOPA is the FWM phenomenon in which two pump photons are degenerately combine with a signal photon at the fiber input, and as a result the amplified signal together with a new frequency component known as the idler emerge the fiber output [11].

In general, FOPAs are classified into two types: one-pump (1-P) and two-pump (2-P) FOPAs. In a 1-P FOPA, a single pump wave is combined with the signal wave at the fiber input, whereas in a 2-P FOPA two pump waves at different wavelengths are initially combined and then are input into the fiber with the signal wave [2]. A 1-P FOPA which is the subject of this paper, has a simpler architecture compared with the 2-P FOPA and is usually used for high-gain amplification of communications signals [3]. The FOPA gain is defined as $G = 10\log\left(\frac{P_{s,out}}{P_{s,in}}\right)$ dB, where $P_{s,in}$ and $P_{s,out}$ are the signal powers at the fiber input and output, respectively. The FOPA gain depends on different parameters such as fiber length and dispersion, pump and signal powers, pump and signal wavelengths, and the nonlinearity of the fiber. The impact of fiber nonlinearity is included in the governing equations of the FOPA via the nonlinear parameter $\gamma = \frac{n_2\omega_0}{cA_{eff}}$ where ω_0 is the center frequency of the pump wave, c is the light speed, n_2 is the nonlinear refractive index and A_{eff} is the effective mode area. The effective mode area is defined as $A_{eff} = \frac{\left(\int\int_{-\infty}^{\infty}\left|F(x,y)\right|^2 dxdy\right)}{\int\int_{-\infty}^{\infty}\left|F(x,y)\right|^4 dxdy}$, where $F(x,y)$ is the transverse distribution of the field or the input pump profile [11].

So far, the pump profile at the FOPA input has been assumed to be Gaussian with the radius w and the effective area of $A_{eff} = \pi w^2$. However, in practice the pump sources used in the telecommunication region are the diode lasers where their outputs are described by Lorentz-Gaussian beams [12]. Assuming an input pump wave with the Lorentz-Gaussian profile instead of the Gaussian is more realistic and hence we anticipate that by modifying the input pump profile $F(x,y)$, the effective mode area A_{eff} and consequently the nonlinear parameter of the fiber γ are modified. Finally, by changing the nonlinear parameter, the FOPA gain is changed, too. Also, we expect that the saturation behavior of the FOPA, which is regarded as the curve of the gain versus the input signal power, is changed as the input pump profile is modified. Therefore, in this article, the impact of the input pump profile on the gain spectrum and the saturation behavior of the FOPA is investigated for the first time for two different profiles: the Gaussian and the Lorentz-Gaussian, and the results of both profiles are compared with each other.

The paper is organized as follows. In Section II, the theoretical framework and governing equations of 1-P FOPAs are discussed and the Gaussian and Lorentz-Gaussian profiles are also introduced. Then in Section III, impact of pump profile on the gain spectrum and the saturation behavior of FOPAs is investigated and it is shown that the Lorentz-Gaussian profile has a higher gain and a lower saturation power compared to those of Gaussian profile. Finally, the article is concluded in Section IV, where the main results are summarized.

II. THEORY

The governing equations of one-pump fiber optical parametric amplifiers for the continuous wave (CW) operation are three coupled amplitude equations as follows [1], [2] and [13]:

$$\frac{\partial A_P}{\partial z} = i\gamma\left(\left|A_P\right|^2 + 2\left|A_s\right|^2 + 2\left|A_i\right|^2\right)A_P + 2i\gamma\, A_s A_i A_p^* \exp(i\Delta\beta\, z) - \frac{1}{2}\alpha A_P \tag{1}$$

$$\frac{\partial A_s}{\partial z} = i\gamma\left(\left|A_s\right|^2 + 2\left|A_i\right|^2 + 2\left|A_P\right|^2\right)A_s + i\gamma\, A_i^* A_p^2 \exp(-i\Delta\beta\, z) - \frac{1}{2}\alpha A_s \tag{2}$$

$$\frac{\partial A_i}{\partial z} = i\gamma\left(\left|A_i\right|^2 + 2\left|A_s\right|^2 + 2\left|A_P\right|^2\right)A_i + i\gamma\, A_s^* A_p^2 \exp(-i\Delta\beta\, z) - \frac{1}{2}\alpha A_i \tag{3}$$

where A_P, A_s and A_i are the pump, signal, and idler amplitudes, respectively; and α is the fiber loss and μ is the nonlinear parameter. * represents the complex conjugate and the linear wave vector mismatch is given by:

$$\Delta\beta = -\frac{2\pi c}{\lambda_0^2} S_0 \left(\lambda_P - \lambda_0\right)\left(\lambda_P - \lambda_s\right)^2 \tag{4}$$

where λ_P, λ_s are the pump and the signal wavelengths, respectively. λ_0 denotes the zero-dispersion wavelength (ZDW) of the fiber and S_0 is the dispersion slope calculated at λ_0.

A Gaussian beam has the field distribution as:

$$F(x,y) = \frac{1}{w^2}\exp\left(-\frac{x^2+y^2}{w^2}\right) \tag{5}$$

where w is the beam waist. Also, the field distribution of the Lorentz-Gaussian beam in the Cartesian coordinate is represented by [12]:

$$F(x,y) = \frac{1}{w_x w_y}\frac{1}{1+(x/w_x)^2}\frac{1}{1+(y/w_x)^2} \times \exp\left(-\frac{x^2+y^2}{w^2}\right) \tag{6}$$

where w is the beam waist of the Gaussian part and w_x and w_y are parameters associated with the width of the Lorentz part in the x and y directions, respectively. In Fig.1, the profile of a Lorentz-Gaussian beam is depicted for $w=1$μm, $w_x=6$μm, and $w_y=2$μm, and it is compared to that of a Gaussian beam. As it is evident, both profiles have approximately the same distribution in the x direction, whereas they differ in the y direction. More particularly, the Lorentz-Gaussian beam is narrower than the Gaussian beam in the y direction which leads to a smaller effective-mode area and hence a larger nonlinear parameter. In addition, Fig. 1 is plotted so that both beams have the same total power, i.e., the same area under the curve.

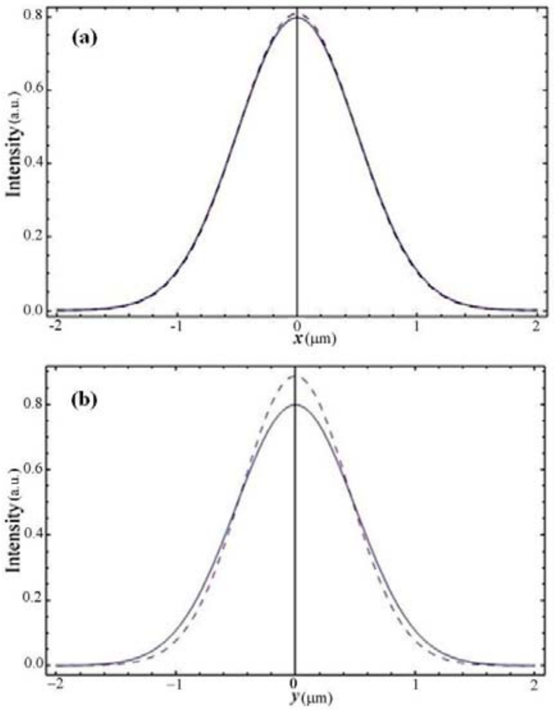

Fig. 1. The profile of the Gaussian beam (solid line) and the Lorentz-Gaussian beam (dashed line) in the x direction (a); and y direction (b) for $w=1$μm, $w_x=6$μm, and $w_y=2$μm.

It should be noted that the fundamental mode of the fiber which can propagate in the fiber is the Gaussian-like mode that is a solution of the Helmholtz equation given a set of boundary conditions. A Lorentz-Gaussian distribution as typically obtained after the facet of a semiconductor laser is therefore very similar to the Gaussian mode as it is evident from Fig. 1. Indeed, the only difference between two beams is that the waist of Lorentz-Gaussian beam is not equal in x and y directions. Therefore, the Lorentz-Gaussian beam can also propagate in the fiber since it is basically a Gaussian beam but with unequal waists in both directions. This is also in agreement with the fact that a real optical fiber is not a perfect cylindrical waveguide since there are always some fluctuations of core diameter along the fiber length which break the symmetry of x and y axes [10].

In the next section, we use Eqs. (5) and (6) for the Gaussian and the Lorentz-Gaussian profiles and investigate the FOPA gain and the saturation behavior for both profiles. Also the results of both profiles will be compared with each other.

III. RESULTS AND DISCUSSION

By solving the coupled amplitude Eqs. (1)-(3) using the Runge-Kutta method, one can simulate the gain spectrum and the saturation behavior of the FOPA. As the simulation parameters, we have used a highly nonlinear fiber (HNLF) with a dispersion slope $S_0 = 0.015\, ps/(nm^2.km)$ at the ZDW of $\lambda_0 = 1560.5\, nm$ [13]. The fiber length and its loss are $L = 500\, m$ and $\alpha = 0.74\, dB/km$, respectively. For determining the nonlinear parameters related to each pump profiles, we use Eqs. (5) and (6) together with the definitions of A_{eff} and γ for a fiber with the core radius of 2μm and the nonlinear refractive index of $n_2 = 2.6\times10^{-20}\, m^2/W$ [14]. Fig. 2 shows the nonlinear parameter of the fiber as a function of the pump wavelength for the Gaussian (solid line) and the Lorentz-Gaussian (dashed line) profiles. As it is seen, at the pump wavelength of $\lambda_P = 1564.0\, nm$, the nonlinear parameter is $\gamma = 33 W^{-1} km^{-1}$ and $\gamma = 37 W^{-1} km^{-1}$ for the Gaussian and Lorentz-Gaussian profiles, respectively. Moreover, the input pump and signal powers are assumed to be $p_P = 25\,dBm$ and $p_s = -40\,dBm$.

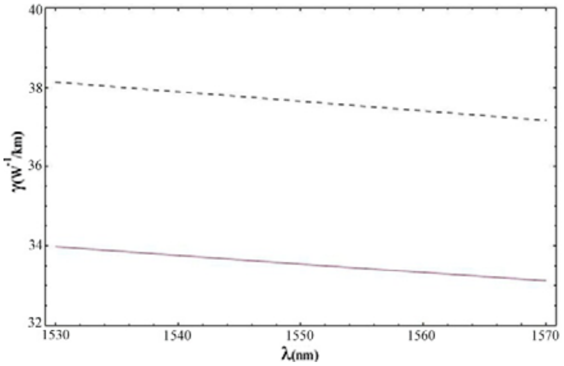

Fig. 2. Wavelength dependence of the fiber nonlinear parameter for the Gaussian (solid line) and the Lorentz-Gaussian (dashed line) profiles.

The gain spectra of the FOPA for two pump profiles, Gaussian (solid line) and Lorentz-Gaussian (dashed line), are shown in Fig. 3. The gain spectra are symmetrically located about the pump wavelength and the gain maxima occur at wavelengths at which the perfect phase matching among the pump, signal, and idler is fulfilled. As it can be seen, the gain is higher for the pump with Lorentz-Gaussian profile compared to that of the Gaussian profile so that at the gain peaks the difference value between two profiles reaches 5 dB. This is because the nonlinear parameter of the Lorentz-Gaussian profile is higher than that of the Gaussian profile.

In Fig.4, the saturation behavior of the FOPA as a function of the input signal power is depicted for the Gaussian (solid line) and the Lorentz-Gaussian (dashed line) profiles. The signal wavelength is $\lambda_s = 1550\,nm$ and as it is seen at weak signal powers (small-signal regime) the gain is almost constant and the gain is gradually decreases with increasing the signal power (saturation regime). This behavior that the gain decreases with the signal power is called saturation, and the signal power at which the gain reduces by 3 dB from the small-signal gain is defined as the saturation power. For example, as it is indicated by vertical lines in Fig. 4, the saturation powers for the Gaussian and the Lorentz-Gaussian profiles are -7 dBm and -10 dBm, respectively. This means that a FOPA with a Lorentz-Gaussian pump goes more quickly to the saturation (i.e., at lower signal powers) than a FOPA with a Gaussian pump. This feature is important for applications in noise suppression and signal processing [8], [15-16].

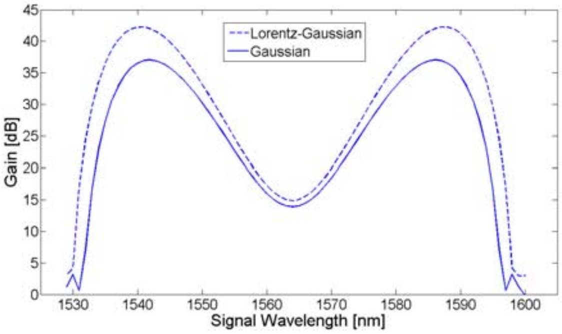

Fig. 3. Gain spectrum of the FOPA for two different pump profiles: Gaussian (solid line) and Lorentz-Gaussian (dashed line).

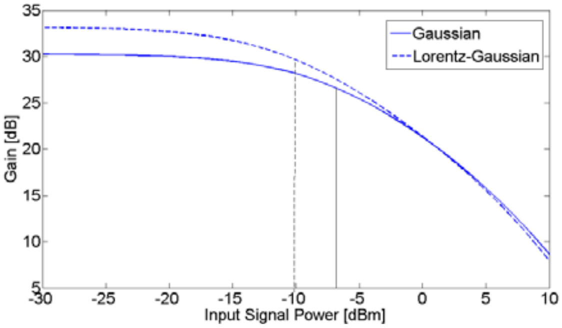

Fig. 4. Gain saturation of the FOPA for two different pump profiles: Gaussian (solid line) and Lorentz-Gaussian (dashed line). Vertical lines indicate the saturation powers for the Gaussian and the Lorentz-Gaussian profiles which take place at -7 dBm and -10 dBm, respectively.

IV. CONCLUSION

We have theoretically investigated the impact of input pump profile on the gain spectrum and the saturation behavior of one-pump fiber optical parametric amplifiers (1-PFOPAs). It was shown that the Lorentz-Gaussian profile has an effective mode area smaller than that of the Gaussian profile. This led to a higher nonlinear parameter and consequently a higher gain with a lower saturation power for the Lorentz-Gaussian profile in comparison with the Gaussian profile. Also, the difference between the gain values of two profiles is maximum at the gain peaks where the phase matching among the interacting waves is perfect. The results of this article provide a more realistic model for 1-P FOPAs since laser diodes which are practically used as the pump sources in telecommunication region exhibit Lorentz-Gaussian profile rather than the Gaussian one.

REFERENCES

[1] J. Hansryd, P.A. Andrekson, M. Westlund, J. Li, and P.O. Hedekvist, "Fiber-based parametric amplifiers and their applications," IEEE J. Sel. Top. Quantum Electron. Vol. 8**,** pp. 506-520, 2002.

[2] M.E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices*, Cambridge University Press, 2007.

[3] T. Torounidis, P.A. Andrekson, and B.E. Olsson, "Fiber-Optical Parametric Amplifier with 70-dB Gain," IEEE Photon. Technol. Lett. Vol. 18, pp. 1194-1196, 2006.

[4] J.M. Chavez Boggio, J.R. Windmiller, M. Knutzen, R. Jiang, C. Bres, N. Alic, B. Stossel, K. Rottwitt, and S. Radic, "730-nm optical parametric conversion from near- to short-wave infrared band," Opt. Express, Vol. 16, pp. 5435-5443, 2006.

[5] S. Watanabe, F. Futami, R. Okabe, and H.G. Weber, "An optical parametric amplified fiber switch for optical signal processing and regeneration," IEEE J. Sel. Top. Quantum Electron. Vol. 14**,** pp. 674-676, 2008.

[6] J. Hansryd and P.A. Andrekson, "Wavelength tunable 40 GHz pulse source based on fiber optical parametric amplifier," Electron. Lett. Vol. 37, pp. 584-585, 2001.

[7] A. Vedadi, A.M. Ariaei, M.M. Jadidi, and J.A. Salehi, "Theoretical study of high repetition rate short pulse generation with fiber optical parametric amplification," IEEE J. Lightw. Technol. Vol. 30, pp. 1263-1268, 2012.

[8] H. Pakarzadeh and A. Zakery, "Modeling of noise suppression in gain-saturated fiber optical parametric amplifiers," Opt. Commun. Vol. 309, pp. 30–36, 2013.

[9] C. Peucheret, M. Lorenzen, J. Seoane, D. Noordegraaf, C.V. Nielsen, L.G. Nielsen, and K. Rottwitt, "Amplitude Regeneration of RZ-DPSK Signals in Single Pump Fiber Optic Parametric Amplifiers," IEEE Photon. Technol. Lett. Vol. 21, pp. 872-874, 2009.

[10] H. Pakarzadeh, M. Bagheri, and A. Keshavarz, "Designing one-pump fiber optical parametric amplifiers for an insensitive amplification to dispersion fluctuation," J. Nonlinear Opt. Phys. Mater. Vol. 23, No. 2 pp. 1450023 (1-12), 2014.

[11] G.P. Agrawal, *Nonlinear Fiber Optics*, 4th ed. Academic Press, 2007.

[12] A. Naqwi and F. Durst, "Focusing of diode laser beams: a simple mathematical model," Appl. Opt**.** Vol. 29, pp. 1780-1785, 1990.

[13] H. Pakarzadeh and A. Zakery, "One-Pump Fiber Optical Parametric Amplifiers: Experiments and Simulations," in Proc. *4th Iranian Conf. on Photon. Eng. ICPE 2012, Tabriz,* pp. 13-16, 2012.

[14] H. Masaaki, "Silica-Based Highly Nonlinear Fibers and Their Application," IEEE J. Sel. Top. Quantum Electron. Vol. 15**,** pp. 103-113, 2009.

[15] K. Inoue and T. Mukai, "Experimental Study on Noise Characteristics of a Gain-Saturated Fiber Optical Parametric Amplifier," J. Lightwave Technol. Vol. 20, pp. 969-974, 2002.

[16] M. Skold, J. Yang, H. Sunnerud, M. Karlsson, S. Oda and P.A. Andrekson, "Constellation diagram analysis of DPSK signal regeneration in a saturated parametric amplifier," Opt. Express, Vol. 16, pp. 5974-5982, 2008.

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