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All Optical Amplifier using Dual-core Fiber in Presence of Linear and Quadratic Intensity-dependent Refractive Index

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Summary

We investigate the effect of quadratic intensity-dependent refractive index in all-optical nonlinear amplifier, based on a dual-core optical fiber coupler of which one core is lossy and another active. The relevant coupled equations for nonlinear coupler are written and numerically solved to predict the output achievable from the active core corresponding to the input injected into the same core. The results reveal some novel and striking effects in amplifier optics showing much brilliant prospect of such nonlinearity over the Kerr case.

1 Introduction

The nonlinearity based different optical-fiber components like optical couplers, switches, optical power filter etc. for all optical components are becoming integral part of fiber-based communication systems [1–4]. In this context tremendous attention has been given on various Kerr and non-Kerr like nonlinearity [5–7] based optical-fiber components. One of such components is the nonlinear optical amplifier based on either nonlinear optical loop mirrors [8] or the recently proposed dual-core fiber [9–10] in which one core supports amplification and another attenuation. It is relevant to mention that the latter kind of nonlinear amplifiers is currently receiving preference with a view to solve problems in separation of pulse and noise in soliton generation and noise filter [11–12]. However, although the dual-core configuration in the latter type has exploited only the Kerr nonlinear self phase modulation, the effect of nonlinearity due to quadratic intensity-dependent refractive index variation in such case has not been reported yet to the best of our knowledge. The appearance of quadratic intensity-dependent nonlinearity in semiconductor doped optical fiber has, recently, been physically explained [5, 7]. In our study we report the propagation characteristics of the linear (Kerr) and quadratic intensity-dependent nonlinear optical fiber amplifier (NOFA) based on dual core amplifier with one active core and another lossy core. The introduction of such type of nonlinearity is shown to produce very interesting and novel effects on power amplification at various input power levels and at various coupling lengths. The results should be useful in the design of optical amplifiers to be employed in digital optical fiber communication systems in the special context of long haul soliton fiber communication for which weak background light between signal pulses is highly undesirable and in design of reduced power all optical switches etc.

2 Theory

The proposed model for the evolution of cw signal in above kind of NOFA with dual cores, one supporting gain and the other loss can be written as

$$i\frac{du}{dz} + N\left(|u|^2\right)u - Kv = i\gamma u \tag{1}$$

$$i\frac{dv}{dz} + N\left(|v|^2\right)v - Ku = -i\Gamma v \tag{2}$$

where $N(I) = I + \alpha I^2$, α is the coefficient of quadratic intensity-dependent nonlinearity. It has both negative and positive values [5]. In this connection it is to be pointed out that in doubly-doped fiber this type of nonlinearity is achieved by doping of fiber with two appropriate semiconductors. One dopant has positive second order nonlinearity ($n_2^{(a)} > 0$) and high saturation intensity ($I_{sat}^{(a)}$) and the other a negative second order nonlinearity ($n_2^{(b)} < 0$) of nearly same magnitude as $n_2^{(a)}$ and a low saturation intensity $I_{sat}^{(b)}$ ($I_{sat}^{(b)} \ll I_{sat}^{(a)}$) or vice-versa. These parameters correspond to the value of α [7] in terms of power P as

$$\alpha = \frac{\left|n_2^{(b)}\right|P}{\left|n_2^{(a)} - \left|n_2^{(b)}\right|\right|I_{sat}^{(b)}} \tag{3a}$$

or

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$$\alpha = \frac{-n_2^{(a)}P}{\left|n_2^{(a)} - \left|n_2^{(b)}\right|\right| I_{sat}^{(a)}}. \quad (3b)$$

In (1) and (2) u(z) and v(z) represent the complex amplitudes of the electromagnetic fields in the two cores at the propagation distance z with K being the coupling constant; Γ and γ are the linear loss and linear gain coefficients in the respective lossy and active cores. It may be noted that the above equations with $\alpha = 0.0$ stand for and explain beautifully the Kerr amplifier's nonlinear characteristics.

In order to transform the (1) and (2) into simpler form, we introduce the new variables [9] as

$$u = \sqrt{P}\cos\theta \exp\left[\frac{i}{2}(\phi + \psi)\right] \quad (4)$$

$$v = \sqrt{P}\sin\theta \exp\left[\frac{i}{2}(\phi - \psi)\right] \quad (5)$$

where P, θ, ϕ and ψ stand for total cw power, power sharing between the cores, the overall phase and the phase difference between the fields in the coupled cores, respectively, all these variables being function of z.

With the above transformations of (4) and (5), (1) and (2) simply reduce to the following three coupled equations for the three variables P, θ and ψ as

$$\frac{dP}{dz} = (\gamma - \Gamma)P + (\gamma + \Gamma)P\cos 2\theta \quad (6)$$

$$\frac{d\theta}{dz} = K\sin\psi - \frac{1}{2}(\gamma + \Gamma)\sin 2\theta \quad (7)$$

$$\frac{d\psi}{dz} = P\cos 2\theta + 2K\cos\psi\cot 2\theta + \alpha P^2\cos 2\theta. \quad (8)$$

The solution of the nonlinear dynamics of the above problem is simple and achieved through numerical simulation by integrating the system of coupled equations (6) to (8). The relevant initial conditions are chosen as it should be [9] as $\theta(0) = 0$, $P(0) = P_{in}$ and $\psi(0) = \pi/2$. Then, with P_{in}, the input power into the active core of the fiber, we have to evaluate the P_{out}, the output power in the same core at any arbitrary coupling length $z = L$, given by

$$P_{out} = |u|^2 = P(L)\cos^2\theta(L). \quad (9)$$

3 Results and discussion

Now our aim will be to study and interpret the output vs input (OVI) characteristics $P_{out}(P_{in})$ through presentation of the graph of relevant gain vs P_{in}. Here P_{out} depends not only on three dimensionless parameters γ, Γ and L as in the Kerr case [9] but also on the strength of the quadratic intensity-dependent nonlinearity coefficient α in addition. It may be recalled in this connection that the main objective in the Kerr case of study reported for the coupling co-efficient K = 1 has been the prediction of suitable values of these parameters so that one can achieve a sharp contrast between attenuation at small input power and amplification at large input power. In fact, it has been observed in the Kerr case that L = π/2 coupler dimension is not favourably as bonafide as L = π case since one does not observe a sharp contrast between attenuation of the weak input and amplification around the threshold region. However, in this case of L = π/2, the best regime has been obtained at γ = 0.5 and Γ = 0.0 where one gets the best possible steepening. In case of L = π coupler, an optimum situation has been fortuitously observed for γ = Γ = 0.5 corresponding to threshold input power of the order of 1.2 units. Up to this value, the attenuation is getting stronger with increase of the input signal power resulting in a weaker output in the same fiber. Above this threshold value, the input shoots the output steeply to practically linear amplification regime with a gain of about 13 dB, pretty enough and safe to regenerate pulses without those of parasitical nature [13]. Keeping the above considerations in mind, our aim is to exploit the quadratic intensity-dependent nonlinearity co-efficient α and explore whether one can attain the achievements in the Kerr case for L = π with much lower input and a better situation for L = π/2 case.

Naturally our analysis is restricted to K = 1 as usual and the values γ = 0.5 and Γ = 0.0 for L = π/2 and γ = Γ = 0.5 for L = π. With these values we have done the numerical simulation [14] of (6)–(8) and depicted our results in Fig. 1 and Fig. 2, respectively. First of all with α = 0.0, the Kerr case, we have cross checked and confirmed that our analysis exactly repeats the earlier results [8] shown by the dashed lines in Fig. 1 and Fig. 2.

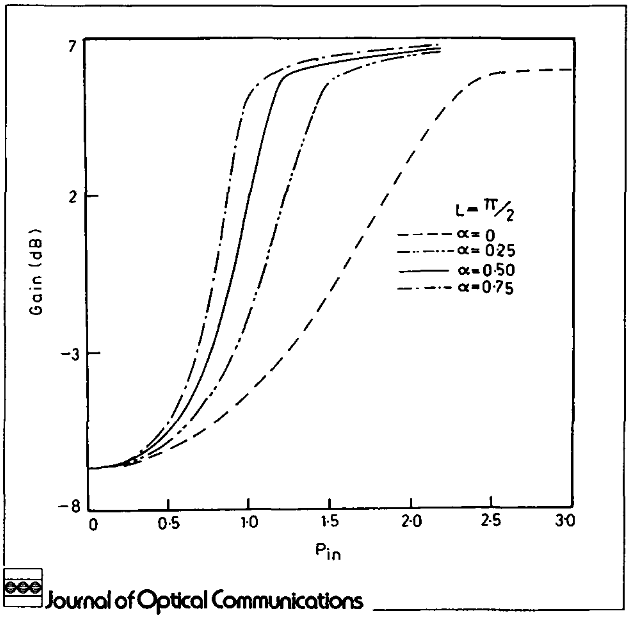

Fig. 1: Output-versus-input characteristic (in decibels) of the nonlinear-optical amplifier with L = π/2, γ = 0.5 and Γ = 0 for α = 0.0 (dashed curve.), α = 0.25 (dash-double dotted) α = 0.5 (solid curve) and α = 0.75 (dash-dotted curve)

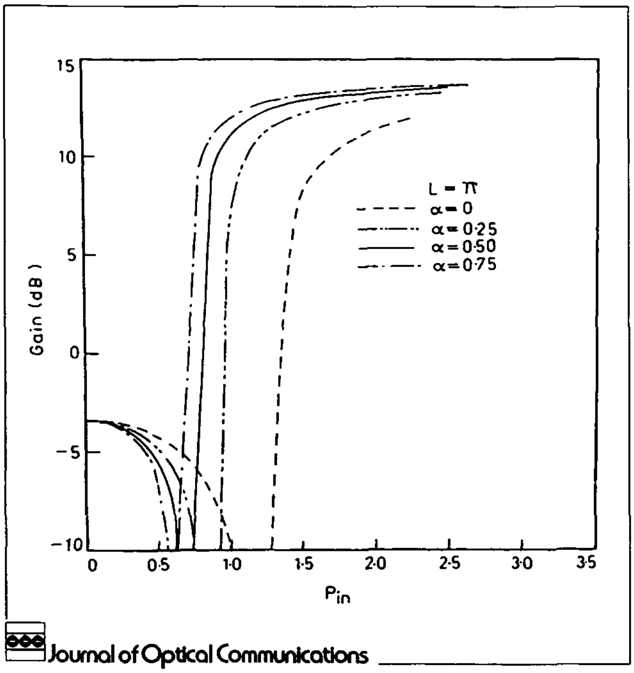

Fig. 2: Output-versus-input characteristic (in decibels) of the nonlinear-optical amplifier with $L = \pi$, $\gamma = 0.5$ and $\Gamma = 0.5$ for $\alpha = 0.0$ (dashed curve), $\alpha = 0.25$ (dash-double dotted), $\alpha = 0.5$ (solid curve) and $\alpha = 0.75$ (dash-dotted curve)

In both the figures dash-double dotted, solid and dash-dotted lines represent the curves for positive value of $\alpha = 0.25$, 0.5 and 0.75 respectively. It may be recalled that with positive linear part the positive values of α in the present case also support the propagation of stable soliton [5] in contrast to the instability caused by negative linear part. As stated earlier we have taken the Kerr case in Fig. 1 for $\gamma = 0.5$, $\Gamma = 0.0$ and $L = \pi/2$ where the amplification is not satisfactorily steepened around the threshold but capable to suppress the weak signal more efficiently than the case of one of the dual cores being lossy ($\Gamma = 0.5$). It is clearly evident from Fig. 1 that the use of quadratic intensity-dependent nonlinearity in such dual cores, one active ($\gamma = 0.5$) and another normal ($\Gamma = 0.0$), not only maintains the similar capability like the Kerr case to suppress the weak signal but also shows two additional prominent features in its favour for device application. Firstly, it is observed that for $\alpha = 0.25$, 0.5 and 0.75 the curves experience more steepening with increase of 'α' just after the threshold input power corresponding to zero gain. Thus the curve for $\alpha = 0.75$ looks more steeper than that for $\alpha = 0.25$ and 0.5 and the latter than that for $\alpha = 0.0$, the Kerr case. The second salient feature observed from the curves is appreciable lowering of threshold input power with the increase of 'α'. In fact, it should be pointed out that a system having a low threshold and thereby operating at low power levels is more attractive from practical point of view. Further it is also verified that for $L = \pi/2$ case the above two features are repeated for $\gamma = \Gamma = 0.5$, an uninteresting Kerr case as reported earlier [9].

We, now, numerically simulate the interesting and promising $L = \pi$ size supported with $\gamma = \Gamma = 0.5$ for $\alpha = 0.25$, 0.5 and 0.75. Here, also we observe the strong favour of adoption of quadratic intensity-dependent nonlinearity in modifying the OVI of NOFA. In comparison to the Kerr case showing sharp transition we observe more pronounced transition showing almost a step like behaviour around the threshold. It is clearly evident from Fig. 2 that addition of quadratic intensity-dependent nonlinearity pushes down the threshold input power appreciably and reaches maximum and better linear amplification regime still around 13 dB after threshold value. These phenomena can be explained as due to variation of nonlinear refractive index between the two cores. The field into the gain input-fiber immediately gets amplified, makes its nonlinear refractive index greater than the other fiber and hence reduces the switching power [15, 16]. Thus lowering of the threshold input power for $L = \pi/2$ and π sizes due to presence of quadratic intensity dependent is a bonus in nonlinear amplifier optics.

Finally it may be added that when similar calculations are repeated for negative values of α, we obtain similar transition but threshold power is observed to be shifted to a much higher value which may be useful for soliton of higher amplitude [7].

4 Conclusions

In conclusion, we report a novel and significant contribution of quadratic intensity-dependent nonlinearity in amplifier optics to modulate the amplification characteristics of nonlinear optical amplifier based on dual core fiber coupler in which one core supports gain while another supports loss. In order to suitably and more excellently control the OVI characteristics, the quadratic intensity-dependent nonlinearity emerges as a significant balancing factor in addition to the other factors, namely, linear gain and dissipation in the two cores, linear coupling between them and nonlinear self-phase modulation. Further, such nonlinearity not only shifts the threshold input power to an appreciably lower value but also facilitates to achieve relatively linear and strong amplification with a much sharper and step-like transition around threshold both at the coupling length and twice of the coupling length respectively.

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