Pump-to-Signal Intensity Modulation Transfer in Saturated-Gain Fiber Optical Parametric Amplifiers

Z. Lali-Dastjerdi, T. Lund-Hansen, K. Rottwitt, M. Galili and C. Peucheret
DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
zoda@fotonik.dtu.dk

Abstract: The pump-to-signal intensity modulation transfer in saturated degenerate FOPAs is numerically investigated over the whole gain bandwidth. The intensity modulation transfer decreases and the OSNR improves when the amplifier operates in the saturation regime.

1. Introduction

Fibre optic parametric amplifiers (FOPAs) offer the possibility for light amplification at arbitrary wavelengths, and are furthermore suitable for numerous optical signal processing applications, such as switching, wavelength conversion, regeneration, pulse generation etc [1]. As parametric amplification is based on the ultrafast Kerr nonlinearity in highly nonlinear fibers and since the maximum signal gain has exponential dependence on the input pump power, small fluctuations of the pump power will instantaneously transfer to the amplified signal and degrade its quality. The pump-to-signal intensity modulation transfer (IMT) is one of the main noise mechanisms in FOPAs [2]. Intensity modulation of the pump arises at low frequencies from the relative intensity noise of the pump laser source. It may also be introduced at higher frequencies (up to a few gigahertz) from phase-to-intensity conversion of the phase modulation introduced to suppress stimulated Brillouin scattering. The pump may even be modulated at higher frequencies in some signal processing applications. To the best of our knowledge, the pump-to-signal IMT has only been investigated theoretically and experimentally in single-pump unsaturated FOPAs in the linear regime, where it was shown that the intensity modulation of the signal could reach 10 times that of the pump, depending on the amplifier gain [3]. On the other hand, it has been experimentally shown that the excess noise and beat noise of the signal induced by amplified spontaneous emission can be suppressed in FOPAs operated in gain-saturation [4].

In this paper, the low frequency pump-to-signal IMT in saturated one-pump phase-insensitive FOPAs is numerically examined for the first time. The IMT behavior over the whole gain bandwidth is studied. The transferred intensity fluctuations to the signal are shown to be suppressed and the optical signal-to-noise ratio (OSNR) is improved when the amplifier operates in the nonlinear regime with saturated signal gain. The results show that, in a single-pump FOPA with 16 dB maximum unsaturated gain, the IMT decreases by 6.6 dB and the OSNR improves by 3.4 dB when the amplifier is saturated.

2. Theory

The IMT magnitude can be evaluated by applying a small amount of modulation to the input pump power:

$$P_p(0,t) = P_{p0}\left(1 + m_p \cos(2\pi\nu_m t)\right)$$

where P_{p0} is the average input pump power, m_p is the modulation depth and ν_m is the modulation frequency. The IMT is defined as the ratio of the output signal relative intensity modulation, r_s, to the input pump relative intensity modulation r_p:

$$IMT\left[dB\right] = 10\log_{10}(r_s/r_p) \quad , \quad r_i = \left\langle \left(P_i(t) - P_{i,avg}\right)^2 \right\rangle \Big/ P_{i,avg}^{\,2} \quad , i = s, p$$

where $P_i(t)$ is the output signal (s) or input pump (p) power and $P_{i,avg}$ is the average value of the power. In numerical simulations the split-step Fourier method [5] is used to solve the generalized nonlinear Schrödinger equation (NLSE):

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A + \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3} = i\gamma|A|^2 A$$

where β_2 and β_3 are the second and third- order dispersion coefficients, respectively, γ is the nonlinear coefficient and α is the loss of the fiber. The initial amplitude is considered as the sum of the intensity modulated pump and the continuous wave signal and has the form of:

$$A(0,t) = \sqrt{P_p(0,t)}\exp(-i\omega_p t) + \sqrt{P_s(0)}\exp(-i\omega_s t)$$

where ω_i is the angular frequency of the pump or signal. Solving the generalized NLSE enables to include all relevant nonlinear effects as well as to accurately predict the saturation behavior by taking into account all waves generated in the parametric processes and their interactions. The intensity modulation of the signal is then evaluated in the time domain by characterization of the temporally varying output signal waveform obtained after bandpass filtering.

3. Results and discussions

The FOPA parameters used in the simulations are the same as in the experimental report presented in [3] that exhibited 16 dB maximum gain for a pump power of 25 dBm and a pump wavelength of 1562.5 nm. Fig. 1 shows the gain spectra of the amplifier at different signal input power levels. The maximum gain decreases from 16 dB in the unsaturated state to 14.5, 13 and 11.5 dB for signal input powers of 1.8, 5.4 and 7.8 dBm, respectively.

Fig. 2 shows the calculated IMT over the gain bandwidth for different signal input powers. The input pump modulation depth is 0.05 for 10 GHz modulation frequency. Clearly, the IMT increases rapidly with increasing wavelength separation between the pump and signal. Signals wavelengths at the outer slopes of the gain spectrum suffer the most from pump-to-signal IMT as the pump power dependence of the gain makes that part of the spectrum more sensitive to the pump intensity fluctuations. The IMT reduces as the signal input power increases and the gain decreases. The IMT reduction is more pronounced for the wavelengths with the maximum unsaturated gain because the saturation power of the FOPA is inversely proportional to the gain [6]. For the signal wavelengths of 1545 nm and 1580.4 nm, at which the maximum unsaturated gain occurs, the IMT decreases by 6.6 dB from 14 to7.4 dB.

The waveforms of the input pump and amplified signals at 1545 nm under different saturation conditions are plotted in Fig. 3(a). One can see that the fluctuations in the signal power follow the pump fluctuations and are significantly enhanced for unsaturated signal gain. This intensity modulation transfer to the signal reduces for higher input signal power levels.

The pump, signal and IMT behaviors with respect to the signal input power for the signal wavelength corresponding to the maximum unsaturated gain (1545 nm) are shown in Fig. 3(b). The IMT magnitude is as low as 2.9 dB when the signal reaches its maximum output power.

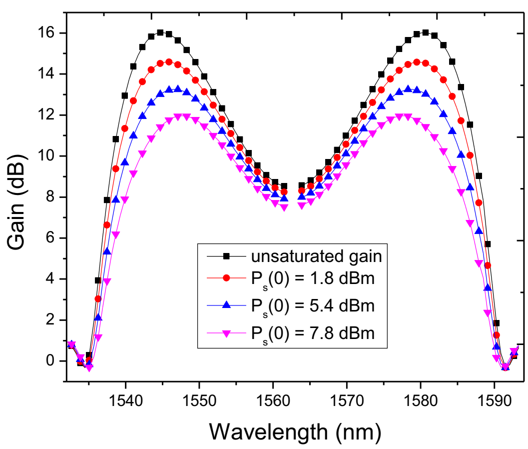

Fig. 1. Signal gain spectra for different signal input power levels.

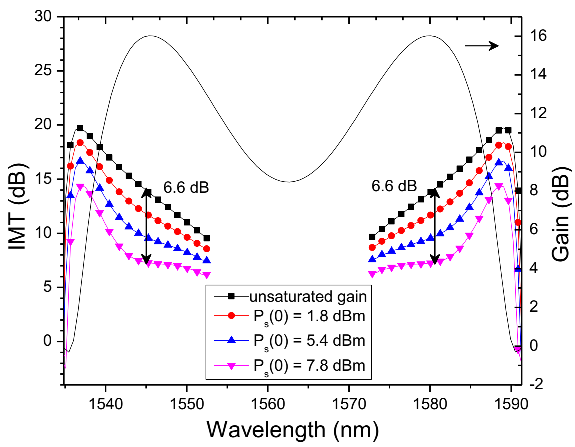

Fig. 2. Wavelength dependence of the IMT under different saturation conditions.

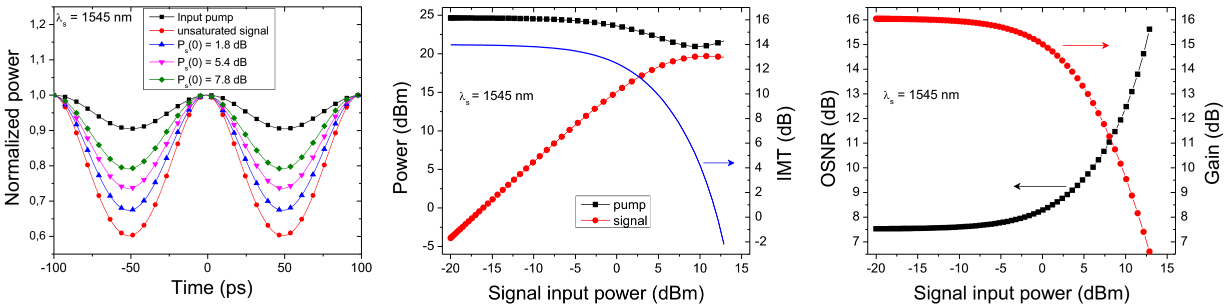

Fig. 3. (a) Waveforms of the input pump and amplified signal for different levels of signal input power; (b) IMT, signal output power and pump output power as a function of signal input power; (c) OSNR and signal gain as a function of signal input power.

In order to quantify the induced improvement of the quality of the amplified signal by operation of the FOPA in saturated conditions, the following definition for the OSNR of the signal is used:

$$OSNR = P_{avg} \Big/ \sqrt{\left\langle \left(P(t) - P_{avg} \right)^2 \right\rangle}$$

Fig. 3(c) shows the signal OSNR and gain as a function of input signal power. The OSNR is at 7.5 dB when the amplifier is unsaturated and has the maximum gain. The signal OSNR improves by 2.2 dB from 7.5 to 9.7 dB when the maximum gain drops by 3 dB to 13 dB.

4. Conclusion

In summary, the pump-to-signal IMT in saturated-gain single-pump FOPAs has been numerically studied for the first time. It has been shown that the IMT from the pump to the signal can be considerably reduced when the FOPA is operated in saturation. In the studied FOPA, the IMT is reduced by 6.6 dB and consequently the OSNR is improved by 2.2 dB.

5. References

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