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Two-pump fiber optical parametric amplifiers: Beyond the 6-wave model

H. Pakarzadeh[a,*], R. Golabi[a], C. Peucheret[b]

[a] Department of Physics, Shiraz University of Technology, Shiraz, Iran
[b] Univ Rennes, CNRS, FOTON – UMR 6082, F-22305 Lannion, France

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ABSTRACT

Two-pump (2-P) fiber optical parametric amplifiers (FOPAs) are a versatile class of FOPAs which can exhibit wide and flat gain spectra in arbitrary wavelength regions, when compared with one-pump (1-P) FOPAs. The 4-wave and the 6-wave models are commonly used to simulate 2-P FOPAs by considering four and six interacting waves, respectively. Although the 6-wave model provides more accurate results than the 4-wave model, it does not take into account higher-order four-wave mixing products (HFPs) especially when the FOPA saturates. The main goal of this paper is to accurately model the 2-P FOPA in which HFPs beyond six interacting waves are included. To this end, the nonlinear Schrödinger equation (NLSE) is solved using the split-step Fourier method and the results are compared with those of previous models such as the 4-wave and 6-wave models as well as an existing analytical solution. The results, which are compared with available experimental data, show that for high input signal levels where the FOPA operates in saturation, the 6-wave model fails to provide accurate simulation results and deviates from results obtained by the NLSE. Therefore, NLSE-based modeling, which includes arbitrary interacting waves beyond the 6-wave model is important for applications in the saturation regime such as signal processing, noise suppression and regeneration.

1. Introduction

Fiber optical parametric amplifiers (FOPAs) have received the attention of many researchers over the past decade due to their potential for applications in optical communication systems such as wavelength-division multiplexing (WDM), signal processing, wavelength conversion and so on [1–5]. The fundamental principle of 2-P FOPA is non-degenerate four-wave mixing (FWM) among the signal, two pumps and idler waves [1–3]. FWM is a nonlinear phenomenon arising from the third-order susceptibility ($\chi^{(3)}$) where the nonlinear interaction between two pumps and signal waves is led to annihilate two pump photons and create a new wave at a different frequency called idler such that the energy and momentum conditions are conserved during parametric interaction. The FWM process is classified into degenerate and non-degenerate types according to input photon frequency. In degenerate FWM process, two pump photons with equal frequencies interact with a signal photon and a new photon known as idler is generated, whereas in non-degenerate FWM the interacting pumps have different frequencies [3,6]. Equivalently, FOPAs are categorized into one-pump (1-P) and two-pump (2-P) FOPAs [2]. Here, we focus on 2-P FOPAs, which are relying on the non-degenerate FWM process.

Fig. 1 shows a 2-P FOPA configuration in which pump 1 and pump 2 are combined together via a fiber coupler (FC). Pumps and signal are then combined together with another FC before being injected to an optical fiber [2,7]. Eventually, at the output of fiber the signal and the new wave (idler) are monitored via an optical spectrum analyzer (OSA).

Two-pump, in contrast with one-pump scheme, can exhibit a wide and uniform gain spectrum [7–10]. This unique feature of 2-P FOPAs can be used in wavelength-division multiplexing (WDM) systems to equally amplify different channels in telecommunication links. Furthermore, in order to increase the number of WDM channels that can be amplified, the amplifier bandwidth should be enlarged and 2-P FOPAs are good candidates for this goal [11–16]. Modeling of 2-P FOPA has been performed based on two models: 4-wave and 6-wave. Simulation results based on the 6-wave model have shown better agreement with available experimental results and exhibit more accurate results [7]. Nevertheless, we expect the 6-wave model to be insufficient when the input signal power increases, resulting in the amplifier being used in saturation. When the FOPA saturates, the number of higher-order FWM products (HFPs) is increased, which in turn leads to the increase of the number of real interacting waves beyond 6 waves. As yet HFPs effects in 1-P FOPAs have only been investigated from the viewpoint of their resulting asymmetric gain spectra due to interaction of HFPs and generated dispersive waves. The presence of difference in gain between the two lobes of the gain spectra of 1-P FOPAs has been studied in a few

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[*] Corresponding author.
E-mail address: pakarzadeh@sutech.ac.ir (H. Pakarzadeh).

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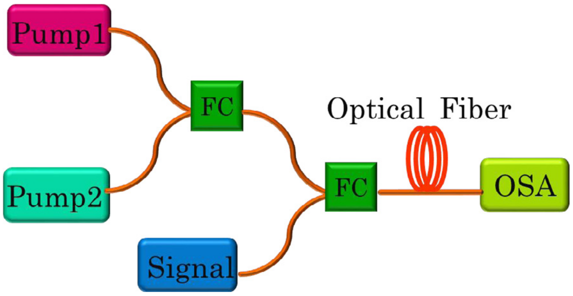

Fig. 1. Schematics of a 2-P FOPA. FC: fiber coupler, OSA: optical spectrum analyzer.

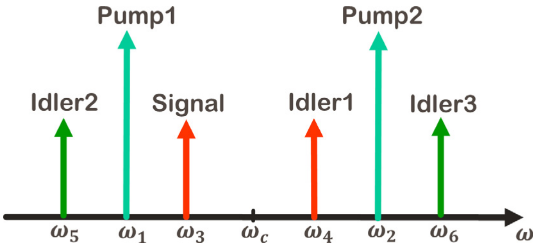

Fig. 2. Frequency assignments of 2-P FOPA based on the 6-wave model.

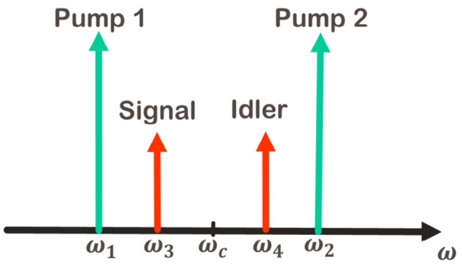

Fig. 3. Frequency assignment of 2-P FOPA based on the 4-wave model.

Table 1
Parameters used for the 2-P FOPA simulations.

Symbol	Parameter	value
λ_1	Pump 1 wavelength	1549.05 nm
λ_2	Pump 2 wavelength	1574.8 nm
P_1	Pump 1 power	21.6dBm
P_2	Pump 2 power	21.6dBm
γ	Nonlinear coefficient	$17[\text{W.km}]^{-1}$
λ_0	Zero-dispersion wavelength	1561.1 nm
α	Fiber attenuation	0.5 dB/km
S_0	Dispersion slope	$0.03\text{ps/nm}^2\,\text{km}$
β_4	Fourth-order dispersion coefficient	$-5 \times 10^{-56}\text{s}^4/\text{m}$
L	Fiber length	500m

papers [17–19]. However, the influence of HFPs on the gain spectra of 2-P FOPAs has not been extensively researched so far. In this paper, 2-P FOPAs are simulated, showing that HFPs beyond 6 waves play an important role in the saturation regime.

The fast response of a saturated FOPA can be used to suppress the fluctuations of input signal power [20–22]. These applications need the FOPA to operate in the saturation regime. Consequently, a proper description of saturated FOPA gain spectrum is essential. In the linear gain regime only first-order FWM products are significant, while in the nonlinear gain regime that results in saturated gain spectra, higher-order FWM products can no longer be neglected [23].

The paper is structured as follows. In Section 2, all models for simulating a 2-P FOPA including analytical solution, 4-wave and 6-wave models as well as the nonlinear Schrödinger equation (NLSE) approach are introduced. Section 3 presents 2-P FOPA simulation results obtained via various models together with related discussion. More specifically, the 2-P FOPA characteristics in the saturation regime are simulated based on the 6-wave and NLSE models, then compared. The role of HFPs beyond the 6-wave model are discussed. Finally, the paper is concluded in Section 4.

2. Theory

The parametric gain, expressed in dB, is defined as $G_s = 10\log\left(\frac{P_s(L)}{P_s(0)}\right)$ where $P_s(0)$ and $P_s(L)$ are the signal power at the input and output of the FOPA, respectively [2,3]. Here, different models for 2-P FOPAs, namely analytical solution, 4-wave and 6-wave models and NLSE are introduced.

2.1. The analytical solution

The analytical solution holds when the pumps are not depleted or equivalently when the signal power is much smaller than the pump power and when fiber loss is ignored. In this case the gain can be

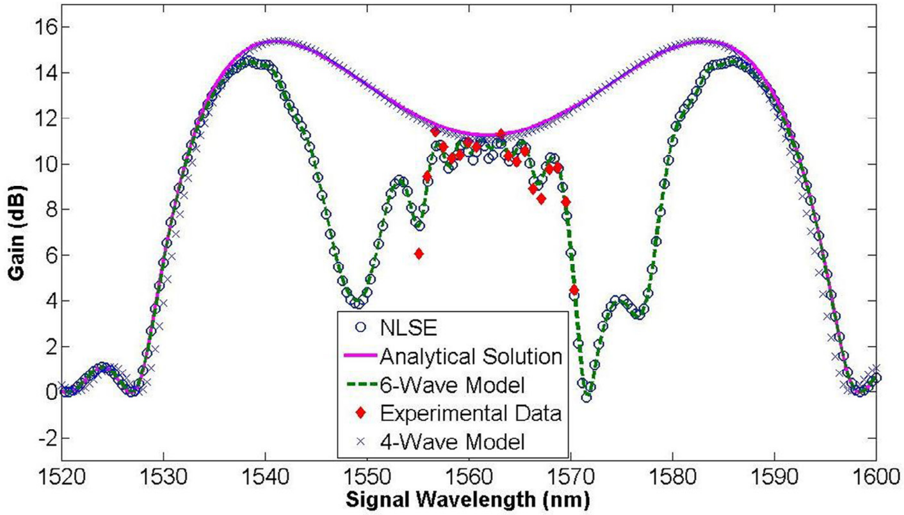

Fig. 4. 2-P FOPA gain spectra in the small-signal regime (the signal input power is − 40 dBm) calculated based on the analytical solution and simulated using the 4-wave and 6-wave models as well as the NLSE method. The experimental data are taken from [26].