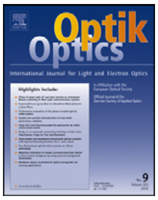
Optik 124 (2013) 906–910

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Four-wave mixing induced gain suppression and noise elevation in a distributed Raman amplifier

Tsu-Te Kung[a,c,*], Chi-Feng Chen[a,b]

[a] Department of Mechanical Engineering, National Central University, Jhongli 32001, Taiwan, ROC
[b] Institute of Opto-Mechatronics Engineering, National Central University, Jhongli 32001, Taiwan, ROC
[c] Department of Electro-Optical Engineering, National United University, Miaoli 36003, Taiwan, ROC

ARTICLE INFO

Article history:
Received 4 October 2011
Accepted 4 February 2012

Keywords:
Four-wave mixing
Distributed Raman amplifier
Raman gain

ABSTRACT

We observed experimentally four-wave mixing (FWM) between 1470 nm pump and 1520 nm signal in a forward-pumped distributed Raman amplifier (DRA) over a 25 km of non-zero dispersion shifted fiber with zero dispersion wavelength of 1495 nm. The 100 mW pump Fabry–Perot (FP) spectrum centered at 1470 nm is reproduced via FWM around the single-wavelength probe signal at 1520 nm, generating spectrally nonuniform FWM induced noise floors. The suppression of Raman gain by about 2.4 dB was also observed with maximum FWM at minimum phase mismatching between pump and signal. The new phase mismatching is derived and combined with the product counts of adjacent pump mode powers to estimate the FWM generated power ratio with maximum and less FWM efficiencies. We find these theoretical calculations are consistent with the experimental results.

1. Introduction

In the wavelength division multiplexed (WDM) optical fiber communication system, distributed Raman amplifier (DRA) has the potential to extend the span length and increase the transmission capacity. It also provides wide band amplification of optical signal in the transmission fiber using multiple high power pumps of different wavelengths, about 100 nm shorter than that of the signal wavelengths [1].

A nondegenerated FWM of three pumps to generate a fourth signal wavelength for forward and backward pumped DRAs was experimentally observed over a 50 km of True Wave (TW) fiber [2]. A degenerated FWM of two pump wavelengths to generate a third signal wavelength for the backward pumped DRA was obtained over an 80 km of TW fiber [3]. Severe degradation of the optical signal-to-noise ratio (OSNR) via elevated noise floors from FWM between pumps and signals was experimentally observed in a bidirectionally pumped DRA over a 100 km non-zero dispersion shifted fiber (NZDSF) with a zero dispersion wavelength lying midway between co-propagating pumps and signals [4]. The maximum nondegenerated FWM generated power ratio between the co-propagated pump Fabry–Perot (FP) modes of a FP laser diode (FPLD) and the single wavelength probe signal in a 25 km of NZDSF was found both in the matching of the group delay between the signal and pump and in the mapping of the signal wavelength to the adjacent FP modes with larger powers of the pump FPLD [5].

In this paper, we investigated nondegenerated FWM between two FP pump wavelengths of a FP laser with multiple longitudinal wavelength modes around 1470 nm and the probe signal of single wavelength around 1520 nm to generate unwanted FP spectra adjacent to the 1520 nm probe signal via FWM in a forward-pumped DRA over a 25 km of NZDSF with zero dispersion wavelength of 1495 nm. The pump FP spectrum centered at 1470 nm was experimentally reproduced via efficient FWM around the 1-mW single-wavelength probe signal at 1520 nm. The suppression of Raman gain by about 2.4 dB was experimentally observed as FWM was maximized for reproduction of FP spectrum at minimum phase mismatching between two FP pump wavelengths and two signal wavelengths.

In our experiment of forward-pumped DRA with the pump operating at pump power of 100 mW, more FWM was observed with lower dispersion of pump and signal wavelengths closer to the fiber zero dispersion wavelength. Less FWM determined by the difference of group indices between pump and signal was also observed in the experiment. The theoretical estimation of the FWM generated power ratio including the product counts of the adjacent pump mode powers was also proved consistently with the experimental results.

This DRA gain suppression together with the reproduced pump FP spectrum at 15xx nm signal band may limit the usefulness of

---

[*] Corresponding author at: Department of Mechanical Engineering, National Central University, Jhongli 32001, Taiwan, ROC. Tel.: +886 37 381727; fax: +886 37 351575.
E-mail address: ttkung@nuu.edu.tw (T.-T. Kung).

0030-4026/$ – see front matter © 2012 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2012.02.023

the forward pumped DRA, generating spectrally nonuniform FWM induced noise floors and crosstalk in WDM fiber optic transmission systems.

2. Theoretical analyses of FWM

Four-wave mixing is a third-order nonlinear parametric process, with the second order nonlinearity very small in an isotropic silica fiber. Significant FWM process occurs only if conservations of photon energy and photon momentum among the four guided optical waves are held. Consider the mixing of two pump photons $hf_{p'}$ and hf_p with a signal photon hf_s to generate a fourth optical photon $hf_{s'}$. To conserve the photon energy, this fourth photon has its optical frequency

$$f_{s'} = f_{p'} - f_p + f_s. \quad (1)$$

The above expression can be written as $\Delta f = f_{s'} - f_s = f_{p'} - f_p$, with the frequency difference in the pump being the same as that of the signal in this nondegenerated FWM.

Let β be the guided wave propagation constant and $n(f_k)$ be the guided wave phase index at the optical carrier frequency f_k, then the corresponding guided wave photon momentum is $\hbar\beta_i = \hbar(2\pi f_i/c)n(f_k)$. The photon momentum conservation for the maximum FWM is just $\Delta\beta = (\beta_{p'} - \beta_p) - (\beta_{s'} - \beta_s) = 0$.

In the wavelength division multiplexing (WDM) system, three waves of frequencies f_i, f_j, and f_k are mixed to generate a new FWM frequency $f_{ijk} = f_i + f_j - f_k$.

The propagation constant difference can be written as [6]

$$\Delta\beta = \beta_{ijk} + \beta_k - \beta_i - \beta_j = \frac{2\pi\lambda_k^2}{c}\Delta f_{ik}\Delta f_{jk}\left[D_c(\lambda_k) + \frac{\lambda_k^2}{2c}(\Delta f_{ik} + \Delta f_{jk})\frac{dD_c(\lambda_k)}{d\lambda_k}\right], \quad (2)$$

where $\Delta f_{mn} = \left|f_m - f_n\right| \quad (m, n = i, j, k)$. The phase mismatch $\Delta\beta$ is affected by the dispersion D_c and dispersion slope $dD_c/d\lambda$ at wavelength λ_k. If the D_c dominates, the contribution of $dD_c/d\lambda$ can be neglected at the wavelength far from zero dispersion wavelength. However, FWM in the zero dispersion wavelength region as discussed in Ref. [7] demonstrated that the $\Delta\beta$ will be affected only by the dispersion slope term. It also can be seen with $D_c(\lambda_0) = 0$ substituted into Eq. (2).

In our work, the FWM is observed between pump and signal wavelength that is about 50 nm apart. In order to discuss the FWM with unequal group indices between pump and signal, we have to keep the group indices of the pump and signal. The FWM is obtained by a multimode FPLD with frequencies f_p, $f_{p'}$ and a probe single wavelength signal with frequency f_s to generate a frequency $f_{s'}$ close by the signal. We expand the propagation constants $\beta_{p'}$ and $\beta_{s'}$ in Taylor series respectively around f_p and f_s and let $N_p(f_{p'}) = N_p(f_p)$ and $N_s(f_{s'}) = N_s(f_s)$, then retaining terms up to the third order in Δf, the propagation constant mismatch can be written as

$$\begin{aligned}\Delta\beta &= (\beta_{p'} - \beta_p) - (\beta_{s'} - \beta_s)\\ &= \Delta\beta_1 + \Delta\beta_2 + \Delta\beta_3,\end{aligned} \quad (3)$$

where

$$\Delta\beta_1 = \frac{2\pi}{c}\Delta f(N_p - N_s), \quad (4)$$

$$\Delta\beta_2 = \frac{\pi}{c}(\Delta f)^2(\lambda_s^2 D_s - \lambda_p^2 D_p), \quad (5)$$

and

$$\Delta\beta_3 = \frac{\pi}{3c^2}(\Delta f)^3\left[(2\lambda_p^3 D_p - 2\lambda_s^3 D_s) + \left(\lambda_p^4\frac{dD_p}{d\lambda_p} - \lambda_s^4\frac{dD_s}{d\lambda_s}\right)\right]. \quad (6)$$

The notations $\Delta\beta_1$, $\Delta\beta_2$, and $\Delta\beta_3$ are the 1st, 2nd, and 3rd order terms respectively from the Taylor expansion of $\Delta\beta$ in terms of Δf. Here N_p and N_s are the group indices respectively for pump and signal. The fiber chromatic dispersion is $D = (1/c)\,(dN/d\lambda)$ and the dispersion slope is $dD/d\lambda = (1/c)\,(d^2N/d\lambda^2)$.

Extending the analysis of FWM [6–8] to the case of two pump waves having identical attenuation α_p to mix with a single-wavelength signal wave with attenuation α_s, we obtain the FWM generated optical power at frequency $f_{s'}$ through a fiber length of L (km) as

$$P_{s'}(L) = \frac{\eta}{9}d^2\gamma^2 P_p P_{p'} P_s\ \exp(-\alpha_s L)(L_{eff}^p)^2, \quad (7)$$

where the effective length for the pump is

$$L_{eff}^p = \frac{1 - \exp(-\alpha_p L)}{\alpha_p}, \quad (8)$$

and the FWM efficiency is

$$\begin{aligned}\eta &= \frac{\alpha_p^2}{\alpha_p^2 + (\Delta\beta)^2}\left\{1 + \frac{4\ \exp(-\alpha_p L)\sin^2(\Delta\beta L/2)}{[1 - \exp(-\alpha_p L)]^2}\right\}\\ &\cong \frac{1}{1 + (\Delta\beta/\alpha_p)^2}.\end{aligned} \quad (9)$$

The notations P_p, $P_{p'}$, and P_s in Eq. (7) are the input powers at frequencies $f_p, f_{p'}$, and f_s respectively. The approximation in Eq. (9) is valid under the condition of $\alpha_p L \gg 1$. The degeneracy factor d equals to 6 for a nondegenerated FWM analyzed here. The nonlinear coefficient γ [9] is

$$\gamma = \frac{2\pi n_2}{\lambda_s A_{eff}}, \quad (10)$$

where A_{eff} is the effective mode field area, λ_s is the vacuum signal wavelength, and n_2 is the nonlinear-index coefficient.

For a maximum FWM efficiency η, the phase mismatch $\Delta\beta$ has to be minimized with the 1st order mismatch $\Delta\beta_1 = 0$. This then implies that the group index of the pump has to be equal to the signal. Thus the dispersions of pump and signal in the 2nd order term in Eq. (5) dominate the phase mismatch.

For the unequal group indices between pump and signal, the difference of group index is difficult to estimate exactly. We can use the maximum FWM with the group index of pump N_p equals to the group signal N_{s0} and substitute into Eq. (4) as

$$\Delta\beta_1 = \frac{2\pi}{c}\Delta f(N_{s0} - N_s) = 2\pi\Delta f \cdot D_s \cdot \Delta\lambda_{s_0,s}, \quad (11)$$

where $\Delta\lambda_{s_0,s} = \lambda_{s0} - \lambda_s$ and D_s is the dispersion evaluated at $(\lambda_{s0} + \lambda_s)/2$.

Assuming random polarization angle between pump and signal, we multiply a factor 1/2 to Eq. (7) and then include the product counts for three adjacent FP wavelengths to obtain the normalized FWM-generated output power ratio at $f_s + \Delta f$ as

$$\frac{P_{s'}^{i+1}(L)}{P_s^i(L)} = \frac{1}{2}\cdot\frac{\eta}{9}d^2\gamma^2(L_{eff}^p)^2(P_p^j P_{p'}^{j-1} + P_p^j P_{p'}^{j+1}). \quad (12)$$

We neglect the contributions from $2\Delta f$ and higher FP frequency spacing, since their contributions to the FWM efficiency in Eq. (9) are at least $\ll$1/4 lower than that of Δf.

3. Experimental setup

Fig. 1 shows the experimental setup. The probe signal was from a mode-locked laser tunable from 1470 to 1580 nm with relative intensity noise (RIN) of −145 dB/Hz. The high power (100 mW) pump laser diode (LD) has multiple FP wavelengths centered at 1470 nm, with its center wavelength stabilized by an external fiber Bragg grating. Fig. 2 shows the FP spectrum of the 1470 nm pump laser with a 0.276 nm mode spacing. The pump FPLD was coupled to a wavelength division multiplexer (WDM) for forward