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Four-wave mixing for nonlinear parameter estimation in a compact ring cavity laser using Bi-EDF

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Abstract
Four-wave mixing is one of the major degradation effects in fiber optic systems with dense channel spacing and low chromatic dispersion on the fiber. In the long-distance wavelength-division multiplexing (WDM) optical communication system, the cross talk generated from four-wave mixing in optical fibers limits the performance of the system, which can be controlled for non-linearity purposes in optical telecommunication, especially the channel wavelengths are set near the zero-dispersion wavelength of optical fibers. Hence, a very short fiber segment with an ultrahigh non-linearity is useful to support the FWM. In this paper, the experimental set-up of compact fiber ring laser based different lengths of nonlinear Bismuth- Erbium doped fiber (Bi-EDF, 181 and 215 cm) is employed by using four-wave mixing (FWM) method. These two gain nonlinear media have been successfully used to stabilize a dual-wavelength fiber laser with and without nonlinear photonic crystal fiber (PCF) at room temperature through the degenerate four-wave mixing effect for γ and n_2 estimation of non-linear parameters and FWM efficiency of optical fiber. The exclusive and practical benefits of using the high non-linear bismuth-erbium doped fiber (Bi-EDF) in implementing a FWM applications for non-linear PCF parameters are experimentally demonstrated. Besides, the FWM effect can be also employed for signal amplification, phase conjugation, wavelength conversion ,and high-speed optical switching. Coupled interaction of Bi-EDF and PCF fiber in FWM scattering explain the unique feature of the proposed configuration.

Keywords
Bi-EDF, Four-wave mixing, Photonic crystal fiber, Non-linear optics .

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1. Introduction

The Four-wave mixing phenomena is one of the major degradation effects in wavelength-division multiplexing (WDM) systems with dense channel spacing and low chromatic dispersion on the fiber. The FWM phase-matching factor is dependent on the signal power. In the long-distance WDM optical communication system, the cross talk generated from four-wave mixing in optical fibers limits the performance of the system, when channel wavelengths are set near the zero-dispersion wavelength of optical fibers. Hence, a very short fiber segment with an ultrahigh nonlinearity to support the FWM [1].

In the Four-wave mixing process, two or more waves interact in a non-linear medium to produce an output at various sum or difference frequencies. The FWM can take place in any material. It refers to the interaction of four waves via the third-order non-linear polarization. When all waves have the same frequency, the process is called degenerate, although their wave vectors are different. This process results from the non-linear index of refraction. One of the most attractive possibilities offered by the high non-linear Bismuth oxide is the opportunity to implement a range of non-linear optical signal processing devices with only a meter or less of the fiber. Some development in highly non-linear bismuth-oxide fiber (Bi-NLF) has resulted in a non-linear coefficient of over 1360 $(\mathrm{W.km})^{-1}$ using a conventional step-index guiding structure [2]. The strongly non-linear PCFs have also been used only to generate new frequencies resulting from four-wave mixing (FWM). In comparison with conventional optical fibers, the significant FWMs in PCFs can occur at relatively low peak powers and over short propagation distances, and such processes can be possible in a much wider wavelength range than 120 nm [3–5]. Recently, Bi-EDF ring lasers have been demonstrated with a tunable single-wavelength operation [6–9]. These lasers provide a wide tuning range as well as a high signal–to-noise ratio. In this letter, we compared two lengths of Bi-EDF in ring fiber laser design for optimum estimation of non-linear

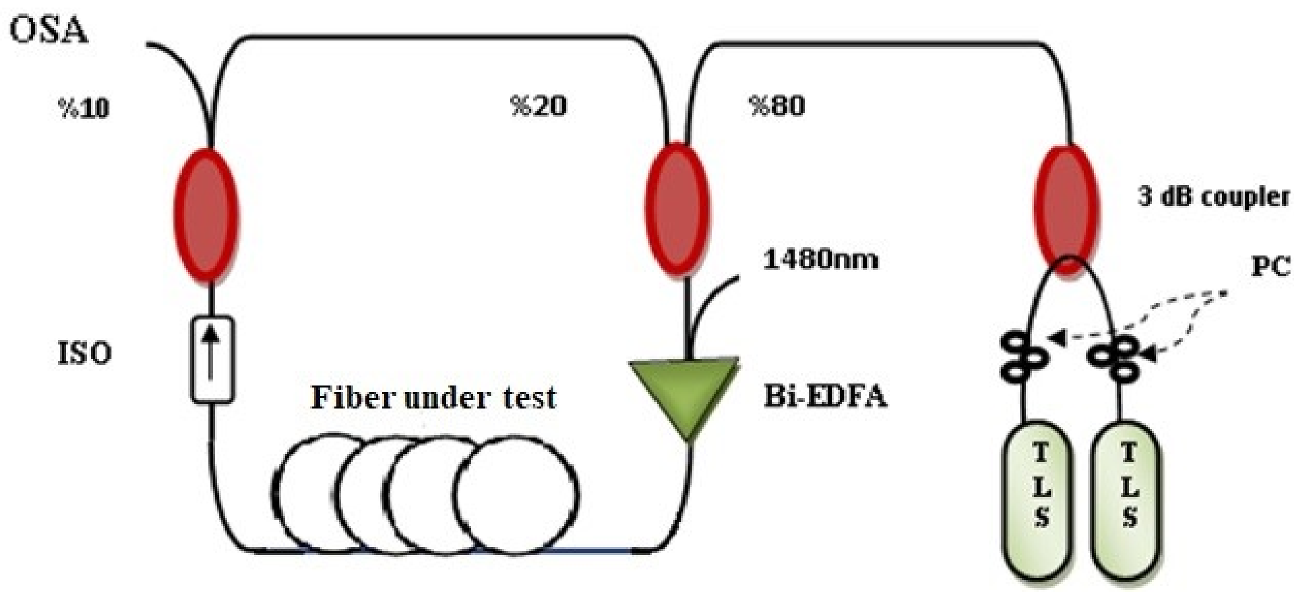

Figure 1. Experimental set-up for FWM in fiber ring laser based different lengths of Bi-EDF.

optical parameters of fiber by employing dual wavelengths in the L band region.

2. Experimental setup

The schematic layout for the proposed dual-wavelength based Bi-EDF is proposed in Fig.1, where a 20 m long non-linear PCF as a fiber under test is compared with two lengths of Bi-EDF in FWM processes. The two long (181 and 215 cm) of Bismuth erbium-doped fiber (Bi-EDF) is optically pumped by a 1480 nm laser diode (LD) through a WDM coupler, and then two signal waves of frequencies TLS_1 and TLS_2 that combine by 3dB coupler enter to the ring by employing 80/20 coupler. Two polarization controllers (PC) were used to set signals into the same polarization state. To ensure that both of the propagating waves had the same polarization, an in-line polarizer, was used. An isolator is employed to block the back reflection of ASE power due to Bi-EDFA in the ring. The 90/10 coupler is also used for monitoring and outputting the laser to an optical spectrum analyzer (OSA).

3. Result and discussion

In this report, two lengths of Bi-EDF with and without PCF are compared in ring fiber laser configuration. As shown in Fig.2, the phenomenon of FWM is very clear when two optical waves at different wavelengths co-propagate in a ring assisted by PCF. Dual-wavelength has been selected very close by 0.3nm spacing. Likely, the presence of PCF generates FWM is due to its unique characteristics. Meanwhile, without PCF, it observed a small idler wave in the right hand with 181cm Bi-EDF. Two signal wavelengths selected in free-running areas of the spectrum without PCF in a ring fiber laser. When at least two optical wavelengths (λ_1, λ_2 ,and λ_3) interact in a nonlinear medium, it will generate a fourth wavelength, λ_4

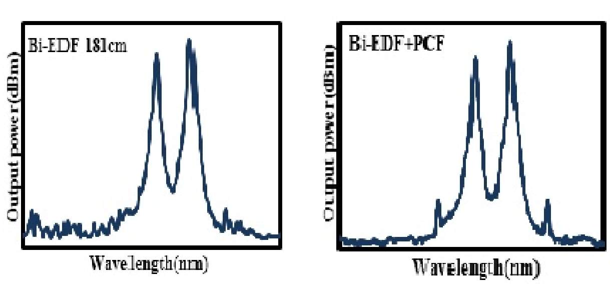

Figure 2. The comparison optical spectrum of dual-signal (λ_1= 1607nm, λ_2 =1607.3nm) FWM from 181 cm of Bi-EDF ring fiber laser with and without the PCF.

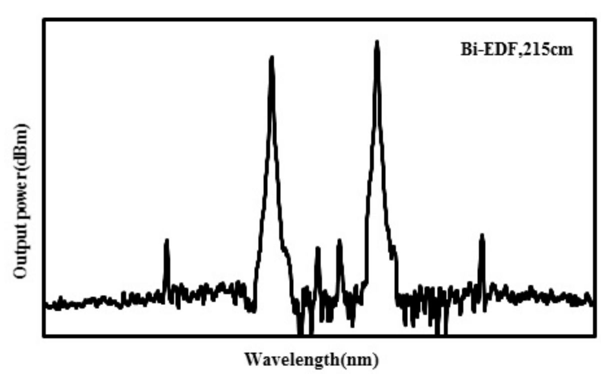

Figure 3. The output spectrum of the CW FWM method in the ring based only 215 cm of Bi-EDF, spacing between two signals (λ_1= 1612nm and λ_2= 1613nm) is 1nm.

where;

$$\lambda_4 = \lambda_1 + \lambda_2 - \lambda_3 \tag{1}$$

Besides that, a combination of two optical waves along a fiber, is viable to produce sidebands at

$$\lambda_{12} = \lambda_{21} = 2\lambda_2 - \lambda_1 \tag{2}$$

These sidebands travel along with the original waves and will grow at the expense of the signal strength input [10].
The existent of optical sidebands can be determined by using the below equation [11, 12];

$$M = N^2 \frac{(N-1)}{2} \tag{3}$$

where N is the number of optical waves pumped into a fiber. When channels are not equally spaced, most FWM components fall in between the channels and add to overall noise [13–15]. Fig.3, shown this situation by employing only 215 cm of Bi-EDFA in the ring fiber laser. In a comparison to the last data, The FWM phenomena have much stronger idlers in this length of Bi-EDF.

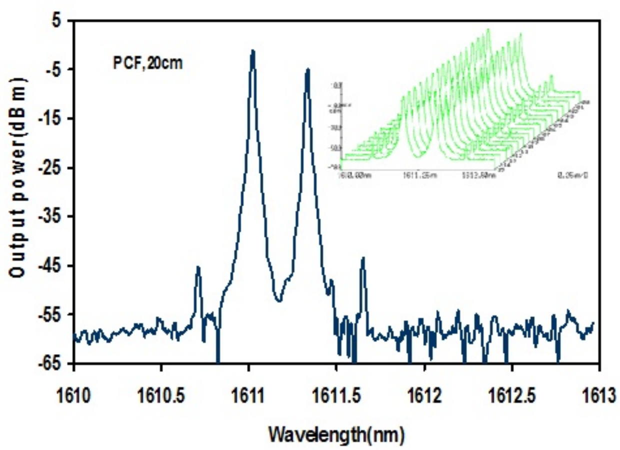

Figure 4. FWM spectra of PCF in free-running area wavelengths, spacing between two signals is 0.3nm. Inset Figure is measured for 30 seconds within the interval time of 15 min.

3.1 Four-wave mixing for γ and n_2 estimation

Non-linear parameter γ and non-linear index coefficient n_2 of non-linear fibers were estimated by four-wave mixing measurements. FWM produces sidebands whose amplitudes and frequencies depend on the non-linear parameter γ. When the pump wave is degenerates, then the power of FWM (or P_{idler}) is described by

$$P_{FWM} = \eta P_S \gamma^2 P_p^2 \frac{1-\exp(-\alpha L)}{\alpha}^2 = \eta P_S \gamma^2 P_p^2 (L_{eff})^2 \tag{4}$$

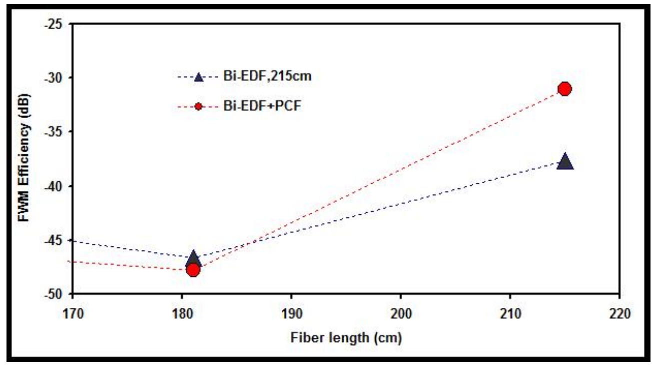

Figure 5. The FWM efficiency as a function of fiber length based Bi-EDF.

where P_P is the input power of the pump wave, P_S is the transmitted power of the signal wave, L is the interaction length of the FWM process, and γ is the fiber non-linear coefficient. The η is the FWM efficiency which depends on the wavelength difference between the pump and signal.
That $\eta = 1$ is confirmed if λ_S is closed enough to λ_P. By replacing the power values due to experimental data in Fig.3, γ achieved around 41.74 ($w^{-1}Km^{-1}$) for 215 cm length of Bi-EDF.
Furthermore, we can also estimate γ for Bi-EDF and other fibers from the below equation [16];

$$P_c \approx \gamma^2 L^2 P_a^2 P_b^2 \tag{5}$$

From this equation with experimental data according to Fig.3, that also obtained γ = 42.26 ($w^{-1}Km^{-1}$). In our previous work, we calculated γ with material parameters of Bi-EDF in the 1550 nm around 58.3($w^{-1}Km^{-1}$) according to the summarized equation [17];

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{6}$$

where λ is the signal wavelength, and A_{eff} represents the effective area of an optical fiber. However, the estimated results according to the (4) and (5) equation-based experimental method is more exact and reliable data.
Furthermore, the powers in the FWM sidebands were measured and used to estimate a value of $n_2 = 3.43 \times 10 - 19$ (m^2/W) according to equation (6) for the test fiber. We also calculated this parameter in the 1550 nm region as well as 4.23×10-19 (m^2/W) that is very close to the experimentally method.
However, the experimentally and systematically errors in single-mode fibers and other components in configuration led to these limited difference values.
Fig.4 shows the FWM spectra in both fibers gain media (215 cm of Bi-EDF and PCF) by optimum spacing 0.3 nm between two signals. FWM of degenerated signal waves appears at the difference between two signal wavelengths. It must be mentioned that the significant FWM like before is observed in 20 m length PCF. The difference peak power of two signal

lasers λ_1 and λ_2 is in interval power 2.9 dB, -3.7 dB, which is due to systematic error of two TLS.

Although the difference peak power of two lasers is more than 2 dB in Figs.4, the stability spectrum for PCF is demonstrated. The inset figure shows the output spectra of PCF in terms of time. Figures exhibit that, the powers of idler waves in PCF and lasing waves are very uniform and stable.

Finally, we compared FWM efficiency with and without PCF in ring configuration based on two lengths of Bi-EDF. The FWM efficiency is defined as [18, 19]:

$$\frac{P_{idler1}}{P_{sig1}^2 P_{sig2}} \tag{7}$$

P_{idler1} is the power of the idler, P_{sig1} and P_{sig2} are the power of output signals. FWM efficiency is plotted in Fig. 5 for two lengths of Bi-EDF with and without PCF.

The maximum FWM efficiency was about -31.07dB for 215cm of Bi-EDF in the L-band region in comparison with 181cm (- 46.68dB) that shows the fiber length dependence of FWM efficiency, especially in this area. By attendance of PCF in our design, FWM efficiency increased with higher long Bi-EDF in this region. This indicates 215 cm of Bi-EDF can be the best candidate with PCF for the L-band applications regarding gain, FWM ,and fusion-splice properties.

4. Conclusion

In brief, the FWM processes were proved in principle and testified in ring cavity-based Bi-EDF for estimation of some non-linear and physical parameters. The experimental results are compared and analyzed for different lengths of non-linear Bi-EDF (181 and 215 cm). The use of a short length of fiber makes it possible to have a rather broad wavelength conversion range despite the use of a fiber with a rather high dispersion value. Tuning of the spectral spacing, input signal power, and the positions of two polarization controllers have been lead to stable spectra. The optimum short fiber length (like 215 cm Bi-EDF) that is used also makes the device more practical in phase-matching conditions and lower pump powers. However, besides of novel applications of the Bi-EDF and PCF that are mentioned practically, the FWM effect can be also employed for signal amplification, phase conjugation, wavelength conversion, and high-speed optical switching. **Conflict of interest statement:**

The authors declare that they have no conflict of interest.

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