Polarimetric four-wave mixing between two wavelengths in a single-mode fiber

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Abstract: We demonstrate experimentally a new polarimetric four-wave-mixing process in a single-mode fiber with two wavelengths. This process can result in polarization-induced crosstalk among WDM channels, yet has potential applications in wavelength conversion.

Four-wave mixing (FWM) is a main concern in the development of long-haul wavelength-division-multiplexed (WDM) communication systems, as nonlinear mixing of multiple wavelengths in a single-mode fiber can produce crosstalk, and hence, degrade the system performance. Recently, we observed a new FWM process in a birefringent fiber, where a distinct frequency-shifted beam was generated as a result of mixing a laser pump and a spectrum of superfluorescent light [1],[2]. Repeating the experiments with a short single-mode fiber, we observed, instead of a frequency-shifted beam, an orthogonal polarization component generated at the pump wavelength [3]. In this paper, we demonstrate this wave-mixing process in a long single-mode fiber with two distinct wavelengths, and discuss its significance in optical communication. Unlike the well-known FWM processes [4]-[7], which are accompanied by the generation of new wavelengths, the present process, when taking place in a single-mode fiber, does not generate any new wavelengths. This may explain why it has escaped scrutiny by system engineers who usually look for new wavelengths from wave mixing.

The principle of nondegenerate polarimetric FWM in a birefringent fiber is illustrated in Fig.1(a), where the x and y axes represent the principal axes of the fiber. In the case of a stimulated process, two waves at the wavelengths λ_1 and λ_2 are mixed to generate two new wavelengths λ_3 and λ_4 and the wavelength shift ($\lambda_1-\lambda_3$ or $\lambda_4-\lambda_2$) is proportional to the polarization-mode dispersion in the fiber [2]. In an ideal single-mode fiber, however, because the polarization-mode dispersion is equal to zero, no new wavelengths should appear. Instead, as shown in Fig.1(b), new orthogonal polarized waves at the original wavelengths are expected. This results in a modification of the polarization states of the waves. In a general non-stimulated process, by launch of three waves into the fiber, the fourth wave can be generated. This suggests that WDM channels can be mixed through this process if their input polarization states, assumed linear, are not perfectly aligned or orthogonal. This mixing effect can give rise to crosstalk if polarization-dependent components are present near the output end of a long fiber link.

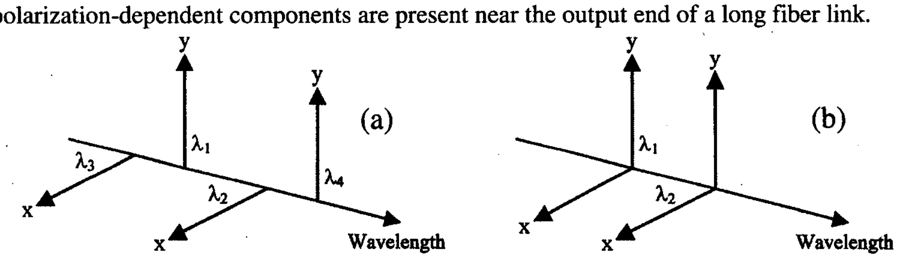

Fig. 1. Illustration of the polarimetric FWM process in (a) a birefringent fiber; (b) a single-mode fiber.

The experimental setup is shown in Fig.2. Light beams from two separate DFB lasers (LD1 and LD2) are amplified respectively and launched into a single-mode fiber via a 3dB directional coupler. The output light from the fiber passes through a tunable band-pass filter and a polarization analyzer (A1) and is measured by a power meter and an electronic spectrum analyzer (ESA) (or a CRO). The output from the other end of the directional coupler is monitored with another polarization analyzer (A2) and an optical spectrum analyzer (OSA). Polarization controllers

(PC1, PC2, PC3, and PC4) are placed at different locations to control the polarization state of light. In our experiments, the wavelengths of light from LD1 and LD2 were fixed at 1548.7nm (λ_1) and 1554.7nm (λ_2), respectively. The input polarization states of the two channels were controlled by PC1 and PC2, respectively, and their polarization relationship was determined by PC3 and A2. The polarization state of the channel selected by the tunable band-pass filter could be restored by PC4 and analyzed by A1. The fiber used was a 6km long dispersion-shifted fiber wound around a spool.

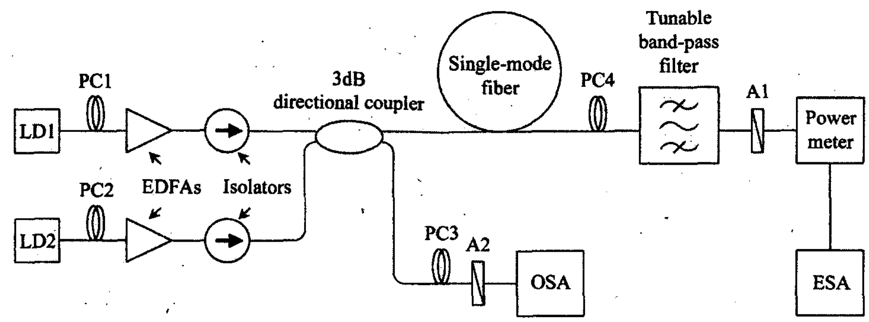

Fig. 2. Experimental setup.

In the first set of experiments, the channel at λ_1 was unmodulated (the CW channel) while the channel at λ_2 was modulated at 75kHz (square wave). When no particular control on the input polarization states of the two channels was given, we observed a 75kHz signal in the output of the CW channel at λ_1 with a magnitude that varied with the setting of A1. This indicated the presence of the wave-mixing effect. The effect was most prominent when the two channels were both linearly polarized with their polarization axes offset by 45°, or when one of the channels was linearly polarized and the other was circularly polarized. On the other hand, when the input polarization states of the two channels were adjusted to have parallel (or orthogonal) linear polarizations, the 75kHz signal in the output of the λ_1 channel disappeared. We next measured the conversion efficiency of the process through comparing the appropriate output polarization components selected by the analyzer A1. The converted power at λ_1 was found to vary linearly with the input power at λ_1, and quadratically with the input power at λ_2, as shown in Fig.3(a) and Fig.3(b), respectively. The results in Fig.3 are given for two cases: (i) "linear + linear": when the two channels were both linearly polarized with their polarization axes offset by 45°; (ii) "linear + circular": when one of the channels was linearly polarized and the other was circularly polarized. There is no significant difference between these two cases, as far as the conversion efficiency is concerned. In this aspect, the present wave-mixing process differs distinctly from the process of nonlinearly induced birefringence. With 8.6mW and 19.9mW input powers at λ_1 and λ_2, respectively, the conversion efficiency measured for the channel at λ_1 was ~1%, which is in reasonable agreement with the theoretical value ~2% that ignores the depolarization effect along the fiber. When the output analyzer A1 was removed, the 75kHz signal at λ_1 disappeared, regardless of the input polarization states of the two channels. This was in fact the result of conservation of energy.

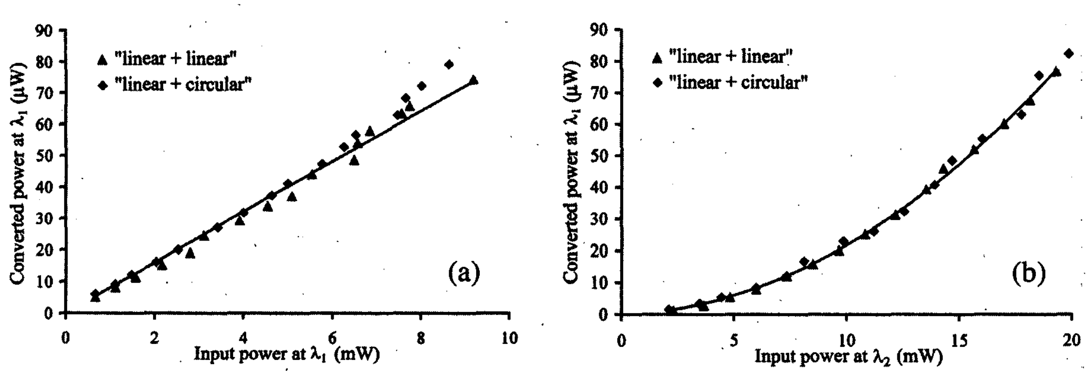

Fig.3. Variations of the converted power at λ_1 with (a) the input power at λ_1 (with the input power at λ_2 fixed at 19.9mW) and (b) the input power at λ_2 (with the input power at λ_1 fixed at 8.6mW) for two input polarization combinations.

In the second set of experiments, the channels at λ_1 and λ_2 were modulated at 35kHz and 30kHz, respectively. To maximize the wave-mixing effect, the input polarization axes of the two channels (linearly polarized) were offset by 45°. The base-band output measured with the electronic spectrum analyzer for the channel at λ_1 is shown in Fig.4(a) for the case with the output analyzer A1 removed, and in Fig.4(b) for the case of using A1 to select the converted component. Ideally, only the modulating frequency 35kHz and its harmonics should be present when the output analyzer A1 was removed. The small signals at 30kHz and the other spurious frequencies shown in Fig.4(a) were due to the polarization dependence of the tunable band-pass filter. The wave-mixing effect can be seen clearly in Fig.4(b), which shows a wide spectrum of frequencies, including the base-band frequencies of the two channels and their harmonics, as well as many other beat frequencies. The output of the channel at λ_2 shows similar characteristics.

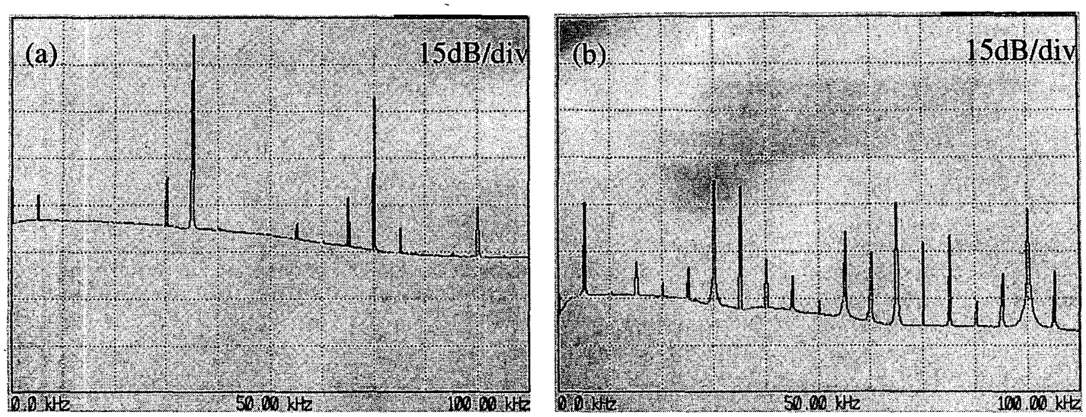

Fig.4. Output from the electronic spectrum analyzer for the channel at λ_1: (a) without output analyzer; (b) with output analyzer.

The salient feature of the polarimetric FWM process demonstrated in this paper is that energy conversion takes place only among the polarization components of the wavelength channels. As a result, no new wavelengths are generated and crosstalk among the channels shows up only when the polarization components of the output light are extracted. To avoid crosstalk of this nature, care must be taken to eliminate polarization dependence along the fiber link. On the other hand, this process could be used for transfer of base-band signals from one wavelength to another wavelength. We have demonstrated a conversion efficiency of ~1% with a 6km long fiber. Furthermore, this process provides a convenient means for monitoring or probing signals carried by one wavelength with another wavelength. This function could find applications in system surveillance. It should also be noted that the process discussed is independent of the wavelength spacing and the dispersion properties of the fiber. In fact, we have obtained practically the same results by using a conventional single-mode fiber (instead of a dispersion-shifted fiber).

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