Polarimetric Four-Wave Mixing in a Single-Mode Fiber

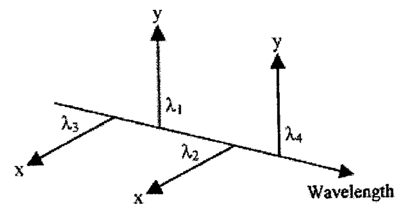
K. S. Chiang, *Member, IEEE*, K. P. Lor, and C. K. Chan, *Member, IEEE*

***Abstract*—We demonstrate a new polarimetric four-wave mixing process in a single-mode fiber with two wavelengths, where energy conversion takes place among the polarization components of the lightwaves. With a 6-km-long fiber, we obtain a conversion efficiency of ~1.2%. Although no new wavelengths can be generated from this process, it can result in polarization-induced crosstalk among wavelength-division-multiplexed channels. On the other hand, this process provides an effective means for transfer of baseband signals from one wavelength to another wavelength, which may find applications in wavelength conversion and system surveillance.**

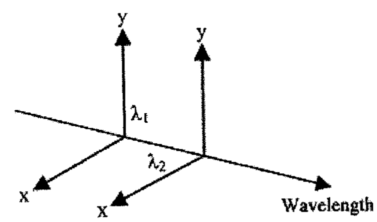
***Index Terms*—Multiwave mixing, optical fiber communication, optical fiber polarization, wavelength-division multiplexing.**

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 (SMF) 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 light [1], [2]. Repeating the experiments with a short SMF, we observed, instead of a frequency-shifted beam, an orthogonal polarization component generated at the pump wavelength [3]. In this letter, we demonstrate this wave-mixing process in a long SMF with two distinct wavelengths and discuss its significance in optical communication. Unlike those well-known FWM processes [4]–[7] that are accompanied by the generation of new wavelengths, the present process, when taking place in an SMF, does not generate any new wavelengths.

The principle of 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 (PMD) in the fiber [2]. In an ideal SMF, however, because the PMD 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 nonstimulated 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 polarization states are not perfectly aligned or orthogonal. This mixing effect can give rise to crosstalk if components with polarization-dependent transmission are used near the output end of a long fiber link.



(a)



(b)

Fig. 1. Illustration of the polarimetric FWM process in (a) a birefringent fiber, (b) an SMF.

Without losing generality, we consider the launch of three waves in an SMF: the x-polarized wave at λ_1 with intensity $I_x(\lambda_1)$, the x-polarized wave at λ_2 with intensity $I_x(\lambda_2)$, and the y-polarized wave at λ_2 with intensity $I_y(\lambda_2)$. By applying the theory of nondegenerate FWM [2], [3], which ignores pump depletion and fiber loss, we obtain an expression for the output intensity of the y-polarized wave at λ_1, namely, $I_y(\lambda_1)$

$$I_y(\lambda_1) = \frac{16}{9}\left(\frac{2\pi}{\lambda_1}\right)^2 \frac{n_2^2}{A_{\text{eff}}^2} I_x(\lambda_1) I_x(\lambda_2) I_y(\lambda_2) L^2 \quad (1)$$

where n_2 is the intensity nonlinear coefficient of the fiber (3.0×10^{-20} m^2/W for a dispersion-shifted fiber (DSF) at 1.5 μm), A_{eff} is the effective area of the fiber core, and L is the length of the fiber. Equation (1) implies that the converted power at λ_1 increases linearly with the input power at λ_1, and quadratically with the input power at λ_2 when $I_x(\lambda_2) = I_y(\lambda_2)$, i.e., the light at λ_2 has equal components in the x and y directions.

To demonstrate the FWM process, we set up the experiment as shown in Fig. 2. Light beams from two separate DFB lasers, LD1 and LD2, were amplified respectively and launched into an SMF via a 3-dB directional coupler. The output light from

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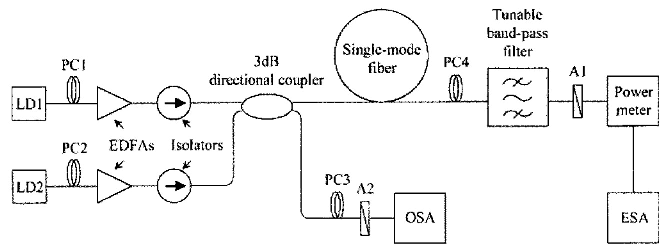


Fig. 2. Experimental setup.

the fiber passed through a tunable bandpass filter and a polarization analyzer, A1, and was measured by a power meter and an electronic spectrum analyzer (ESA) (or a CRO). The output from the other end of the directional coupler was monitored with another polarization analyzer, A2, and an optical spectrum analyzer (OSA). Polarization controllers, PC1, PC2, PC3, and PC4, were placed at different locations to control the polarization state of light. The wavelengths of light from LD1 and LD2 were fixed at 1548.7 and 1554.7 nm, respectively, which are denoted here as λ_1 and λ_2, respectively. The input polarization states of the two channels were controlled independently by PC1 and PC2, and their polarization relationship was determined by PC3 and A2. The polarization state of the channel selected by the tunable bandpass filter was restored by PC4 and analyzed by A1. The fiber used was a 6-km-long DSF wound around a spool.

In the first set of experiments, the channel at λ_1 was unmodulated [the continuous-wave (CW) channel] while the channel at λ_2 was modulated at 75 kHz (square wave). When no particular control on the input polarization states of the two channels was made, we observed a 75-kHz 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. When the input polarization states of the two channels were adjusted to have either parallel or orthogonal linear polarizations, the 75-kHz signal in the output of the λ_1 channel disappeared. These observations agree with the process illustrated in Fig. 1(b). When the output analyzer A1 was removed, the 75-kHz signal at λ_1 virtually disappeared, regardless of the input polarization states of the two channels. This was the direct result of conservation of energy.

We next varied the input powers of both channels independently and measured the converted power at the output of the fiber. The converted power at λ_1 was found to increase linearly with the input power at λ_1, and quadratically with the input power at λ_2, as shown in Fig. 3(a) and (b), respectively. The results in Fig. 3 are given for two cases: 1) "linear + linear": when the two channels were both linearly polarized with their polarization axes offset by 45° and 2) "linear + circular": when the channel at λ_1 was linearly polarized and the channel at λ_2 was circularly polarized. There is no significant difference between these two cases, as far as the conversion efficiency is concerned.

The slope of the straight line in Fig. 3(a) gives a conversion efficiency of ~0.0085 at λ_1 with 19.9-mW input power at λ_2. Because the input powers were measured at the output of the directional coupler, the actual powers coupled into the fiber were smaller. The fraction of light power coupled into the fiber from the directional coupler (the coupling efficiency) was measured to be ~0.73. The actual conversion efficiency should, therefore, be 0.0085/0.73 ≅ 0.012. On the other hand, the conversion efficiency η can be estimated from the following equation, which takes into account the fiber loss and the coupling efficiency

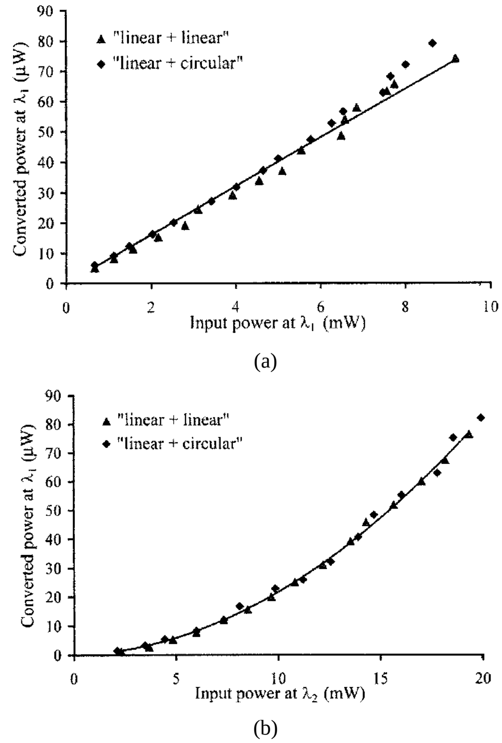
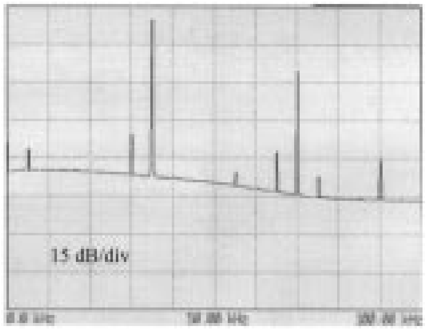


Fig. 3. Variation of the converted power at λ_1 with (a) the input power at λ_1 (with the input power at λ_2 fixed at 19.9 mW) or (b) the input power at λ_2 (with the input power at λ_1 fixed at 8.6 mW) for two input polarization combinations.

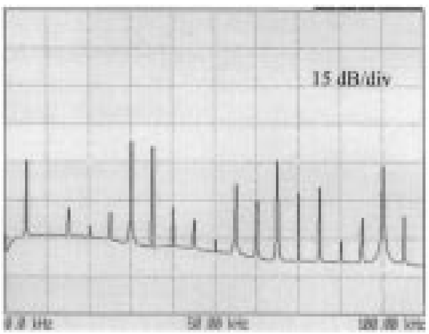
$$\eta = c^2 \left(\frac{L_{\rm eff}}{L}\right)^2 \exp(-2\alpha L)\eta_{\rm ideal} \tag{2}$$

where c is the coupling efficiency, 2α is the fiber power loss in neper, $L_{\rm eff} = [1-\exp(-2\alpha L)]/2\alpha$ is the effective length of the fiber, and $\eta_{\rm ideal} \equiv I_y(\lambda_1)/I_x(\lambda_1)$ is the ideal conversion efficiency calculated from (1). With $I_x(\lambda_2) = I_y(\lambda_2) = 0.5 \times 19.9$ mW, $L = 6$ km, and $A_{\rm eff} = 40\ \mu{\rm m}^2$, we find from (1) $\eta_{\rm ideal} = 0.059$. With a coupling efficiency of 0.73 and a fiber loss of 0.2 dB/km (nominal value given by the fiber supplier), we obtain from (2) a conversion efficiency of ~1.8%, which agrees reasonably well with the experimental value ~1.2%, considering that our calculation ignores the depolarization effect along the fiber. Depolarization along the fiber tends to destroy the optimal polarization relationship between the two channels and, hence, reduce the conversion efficiency.

In the second set of experiments, the channels at λ_1 and λ_2 were modulated at 35 and 30 kHz, respectively. To maximize the wave-mixing effect, the input polarization axes of the two channels (linearly polarized) were offset by 45°. The baseband 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



(a)



(b)

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

frequency 35 kHz and its harmonics should be present when the output analyzer A1 was removed. The small signals at 30 kHz and the other spurious frequencies shown in Fig. 4(a) were due to the polarization dependence of the tunable bandpass filter. The wave-mixing effect can be seen clearly in Fig. 4(b), which shows a wide spectrum of frequencies, including the baseband 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.

As the present FWM process does not generate any new wavelengths, it looks like the effect of nonlinearly induced birefringence, which could also change the polarization state of a propagating beam. We should emphasize that the present process is different from the effect of nonlinearly induced birefringence, because the former, as described by (1) and illustrated in Fig. 1(b), arises from the wave-mixing term $E_x(\lambda_1)E_x(\lambda_2)E_y(\lambda_2)^*$ [2], [8], whereas the latter refers to the cross-phase modulation (XPM) terms $E_i(\lambda_m)|E_j(\lambda_n)|^2$ ($m \neq n$ or $i \neq j$) [8], where $E_i(\lambda_m)$ is the electric field in the i (x or y) direction at the wavelength λ_m ($m = 1$ or 2). We believe that nonlinearly induced birefringence did not play any significant role in our experiments. Unlike the conditions in a conventional Kerr shutter [8], the two wavelengths in our experiments had weak and comparable intensities, and, therefore, similar amounts of birefringence should be induced in the fiber by the two channels but along their respective polarization axes. Because the fiber used was long and the nonlinearly induced birefringence was much smaller than the intrinsic birefringence of the fiber (random in nature), the polarization states of the two channels could not be preserved along the fiber. As a result, the effect of nonlinearly induced birefringence should be averaged out. Furthermore, we observed practically the same conversion efficiency at λ_1, whether the channel at λ_2 was linearly polarized with its polarization axis at 45° from that of the channel at λ_1 or circularly polarized (see Fig. 3). Our observation agrees with the FWM theory, but cannot be explained by the effect of nonlinearly induced birefringence. Experimental results of similar nature reported previously have been explained as the effect of polarization modification by XPM, which is based on solving Manakov's equation [9], [10]. A detailed comparison of our FWM model and the XPM model [9] could lead to a deeper insight into the relationships among various nonlinear processes in an SMF.

In conclusion, the salient feature of the polarimetric FWM process is that energy conversion takes place only among the polarization components of the wavelength channels. 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. This process can also degrade the performance of polarization-division multiplexing for WDM soliton transmission [9]. On the other hand, this process can be used for transfer of baseband signals from one wavelength to another wavelength. We have demonstrated a conversion efficiency of $\sim$1.2% with a 6-km-long fiber. Furthermore, it provides a convenient means for monitoring or probing signals carried by one wavelength with another wavelength. This function may find applications in system surveillance.

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