Polarization Independent Wavelength Conversion Using Fiber Four-Wave Mixing with Two Orthogonal Pump Lights of Different Frequencies

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Abstract—This paper describes polarization independent wavelength conversion, utilizing fiber four-wave mixing. By using two orthogonal pump lights having different frequencies, the baseband signal of the wavelength converted light is insensitive to the polarization state of the original signal light. Experiments that include bit error measurements confirm the polarization independent operation.

I. INTRODUCTION

WAVELENGTH conversion is expected to play an important role in future WDM based optical networks. With converters, optical frequency addressing or routing systems will be flexible and simplified. Several conversion schemes have been proposed to date, utilizing optically triggered multielectrode LD's [1], gain saturation in LD amplifiers [2], [3], oscillation frequency shift induced by external light injection [4], injection locking [5], four-wave mixing (FWM) in LD amplifiers [6], [7] and FWM in optical fibers [8]. However, most of them are sensitive to the polarization state of signal light, which is not preferable for practical applications. One work demonstrated polarization insensitive wavelength conversion, using fiber FWM with a looped configuration [9].

This paper presents a novel technique for polarization insensitive wavelength conversion. Fiber FWM is also utilized with two orthogonal pump lights having different frequencies. Although the generation process itself depends on the polarization states, the polarization insensitiveness is obtained, in effect, at the baseband stage in IM/DD systems. Compared with the previous polarization insensitive method [9], the present system has a simple configuration and higher efficiency. The principle is described in Section II, and experiments are described in Section III. In the experiments, the baseband signal level is constant within 0.5 dB irrespective of the polarization state of signal light, and the conversion operation is confirmed by measuring the bit error rate.

II. MECHANISM

The basic configuration of the proposed conversion scheme is shown in Fig. 1. Two pump lights having different frequencies (f_p and $f_p + \Delta f$) are multiplexed by a polarization beam
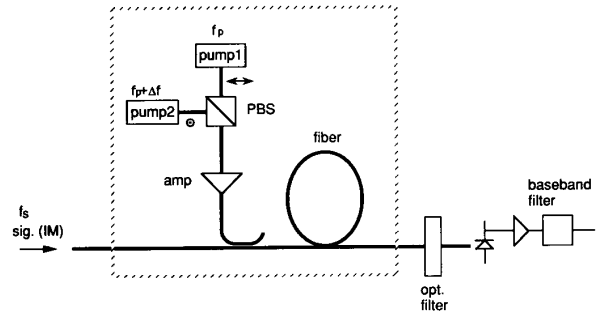
Fig. 1. Configuration of wavelength converter.

splitter (PBS), and then input into a conversion fiber, together with an intensity modulated signal light of frequency f_s. The frequency difference (Δf) is set larger than the data rate of the signal, and the power levels are set identical to the two pump lights.

The FWM interaction occurs in the conversion fiber. This is described by [10]

$$\hat{E}_{\mathrm{FWM}} = \kappa \left[\hat{E}_p \cdot \hat{E}_s^* \right] \hat{E}_p. \tag{1}$$

Here $\hat{E}_p$, $\hat{E}_s$, and $\hat{E}_{\mathrm{FWM}}$ are two-dimensional vectors representing light fields of the pump, signal, and FWM lights, respectively, κ is a proportional constant representing FWM efficiency, and [•] denotes the inner product of the two vectors. The pump light is composed of two orthogonal lights having frequencies f_p and $f_p + \Delta f$, which are written as

$$\hat{E}_p = A_{p1} \exp\left[i2\pi f_p t \right] \hat{e}_1$$
$$+ A_{p2} \exp\left[i2\pi (f_p + \Delta f) t \right] \hat{e}_2. \tag{2}$$

Here A_{p1} and A_{p2} are amplitudes, and $\hat{e}_1$ and $\hat{e}_2$ are unit vectors representing the polarization states, for orthogonal lights 1 and 2, respectively. Vectors $\hat{e}_1$ and $\hat{e}_2$ satisfy the following relations.

$$[\hat{e}_1 . \hat{e}_2^*] = 0 \tag{3a}$$
$$[\hat{e}_1 . \hat{e}_1^*] = [\hat{e}_2 . \hat{e}_2^*] = 1. \tag{3b}$$

Since an arbitrary vector can be expressed by a set of orthogonal unit vectors, the signal light field is expressed as

$$\hat{E}_s = \{ A_{s1} \hat{e}_1 + A_{s2} \hat{e}_2 \} \exp\left[i2\pi f_s t \right]. \tag{4}$$

A_{s1} and A_{s2} are expansion coefficients, which depend on the polarization state of the signal light. Substituting (2) and (4) into (1) with (3a) and (3b), the following equation is obtained.

$$\hat{E}_{\text{FWM}} = \kappa \{ A_{p1}^2 A_{s1}^* \exp[i2\pi(2f_p - f_s)t]$$
$$+ A_{p1} A_{p2} A_{s2}^* \exp[i2\pi(2f_p + \Delta f - f_s)t]\} \hat{e}_1$$
$$+ \kappa \{ A_{p2}^2 A_{s2}^* \exp[i2\pi(2f_p + 2\Delta f - f_s)t]$$
$$+ A_{p1} A_{p2} A_{s1}^* \exp[i2\pi(2f_p + \Delta f - f_s)t]\} \hat{e}_2. \tag{5}$$

FWM lights are generated at $2f_p - f_s, 2(f_p + \Delta f) - f_s$, and $2f_p + \Delta f - f_s$ as shown above.

After being selected by an optical filter, this FWM light is directly detected. The generated photocurrent S is written as

$$S = k' |\hat{E}_{\text{FWM}}|^2$$
$$= k \Big\{ |A_{p1}^2 A_{s1}^*|^2 + |A_{p1} A_{p2} A_{s2}^*|^2$$
$$+ 2|A_{p1}^3 A_{p2} A_{s1}^* A_{s2}^*| \cos(2\pi \Delta f t + \phi) \Big\}$$
$$+ k \Big\{ |A_{p2}^2 A_{s2}^*|^2 + |A_{p1} A_{p2} A_{s1}^*|^2$$
$$+ 2|A_{p1} A_{p2}^3 A_{s1}^* A_{s2}^*| \cos(2\pi \Delta f t - \phi) \Big\} \tag{6}$$

where k' and k are proportional constants, including the O/E conversion efficiency, and ϕ denotes the phase of $A_{p1}^* A_{p2} A_{s1} A_{s2}^*$. Provided that the two pump lights have the same power level as $|A_{p1}|^2 = |A_{p2}|^2 = P_0$, (6) is rewritten as

$$S = k P_0^2 \Big[2 \Big\{ |A_{s1}^*|^2 + |A_{s2}^*|^2 \Big\}$$
$$+ 2|A_{s1}^* A_{s2}^*| \{\cos(2\pi \Delta f t + \phi) + \cos(2\pi \Delta f t - \phi)\} \Big]$$
$$= 2 k P_0^2 \Big[P_s + 2|A_{s1}^* A_{s2}^*| \cos\phi \cos(2\pi \Delta f t) \Big] \tag{7}$$

where $P_s = |A_{s1}|^2 + |A_{s2}|^2$ is the power of the original signal light. Note that the second term is dependent on the polarization state since A_{s1} and A_{s2} depend on that.

Equation (7) indicates that the photocurrent consists of the baseband signal component and the beat component of frequency Δf. Since Δf is larger than the data bit rate, as assumed before, the beat component is eliminated through the baseband filter. Thus, after the filter, the baseband signal is obtained as

$$S = 2 k P_0^2 P_s. \tag{8}$$

This equation shows that the baseband signal is independent of the polarization states. Therefore, polarization insensitive wavelength conversion is achieved, in effect, by regarding the FWM lights at $2f_p - f_s, 2(f_p + \Delta f) - f_s$, and $2f_p + \Delta f - f_s$ as the wavelength converted light. Note that this conversion scheme can be only applied to IM/DD systems.

III. EXPERIMENT

Experiments were carried out to confirm the above mechanism. Two pump lights from DFB-LD's were multiplexed by a polarization beam splitter and then input into a 20 km dispersion-shifted fiber after being boosted by a fiber amplifier. The pump light wavelength was 1551 nm, which was matched
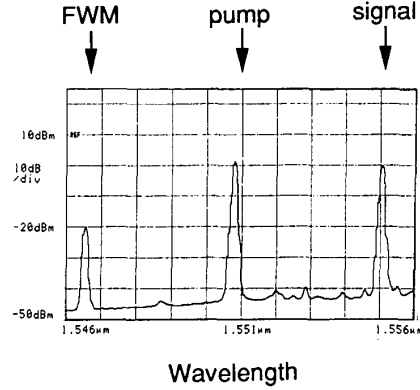

Fig. 2. Optical spectrum at fiber output.

to the zero-dispersion wavelength of the dispersion-shifted fiber, resulting in a wide conversion range [11]. At the same time, an intensity-modulated signal light whose wavelength was 4.2 nm different than the pump lights, was input into the same fiber. The total input power levels were 9.3 dBm for the pump lights and 7.5 dBm for the signal light. The optical spectrum at the fiber output is shown in Fig. 2. A wavelength converted light was generated with a power level of -20 dBm, which scarcely changed with the polarization state of the signal light.

The converted light was selected by cascaded interference filters and then directly detected. The electrical spectra after the detection are shown in Fig. 3. The signal light was modulated with a fixed pattern of (1, 0) at 622 Mb/s, and the frequency difference of the pump lights was set at 1.8 GHz. The polarization state of the signal light was adjusted such that it matched the polarization state of one of the pump lights in Fig. 3(a) and is an intermediate state between those of the two pump lights in Fig. 3(b). The broad peaks around 1.8 GHz represent the beat component appearing in the second term in (7), which depends on the polarization state as shown in Fig. 3. Ideally, the beat component should be zero when the polarization state of the signal light completely matches that of one of the pump lights, though it is not in Fig. 3(a), due to a slight misadjustment of the polarization state. On the other hand, the sharp peak at 311 MHz represents the baseband signal level, which is constant within 0.5 dB, irrespective of the polarization state. This result indicates the polarization insensitive operation at the baseband stage.

The same measurement was also carried out for pseudorandom pattern modulation. The result is shown in Fig. 4. The beat spectrum around 1.8 GHz spreads due to the random modulation. When the two pump light frequencies are close together, a part of the beat spectrum overlaps onto the baseband frequency region and interferes with the desired signal. Thus, the frequency difference between the pump lights should be carefully chosen.

In order to confirm the conversion operation, the bit error rate (BER) was measured after the baseband filter. The original signal light was modulated with NRZ $2^{15} - 1$ PRBS at 622 Mb/s. During the measurements, the polarization state
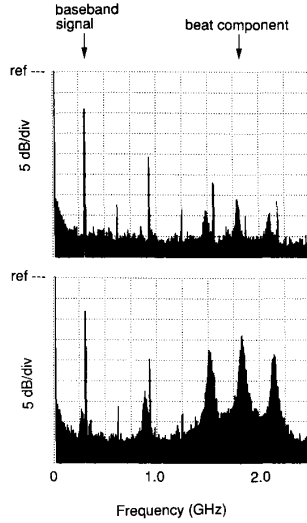
Fig. 3. Electrical spectra after detection for wavelength converted light. Polarization state of signal light matches that of one of pump lights (a),and half matches that of each pump. Original signal is modulated with fixed pattern of (1, 0) at 620 Mb/s. Broad peaks around 1.8 GHz represent the beat component between FWM lights at different frequencies, and sharp peak at 311 MHz represents baseband signal level.
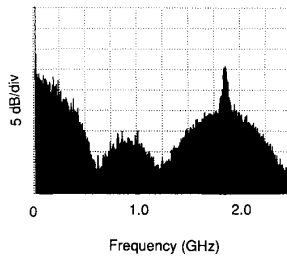

Fig. 4. Electrical spectrum after detection for wavelength converted light. Original signal is modulated with random pattern at 622 Mb/s.

of the signal light was adjusted to generate the maximum beat component, as in Fig. 3(b), in order to examine the worst condition of the system performance. Various values of the pump frequency difference were examined. The result is shown in Fig. 5, where the crosses, triangles, and squares denote BER's for the pump frequency difference of 1.9 GHz, 1.4 GHz, and 1.0 GHz, respectively. The circles are BER's for the original signal light. For a large frequency difference in the pump lights, no degradation was induced and the conversion operation was successfully demonstrated. On the other hand, a penalty occurred for a narrow frequency separation, which is predicted from the spectrum shown in Fig. 4. It is concluded from Fig. 5 that the frequency difference between the pump lights should be three times larger than the data rate.

IV. DISCUSSION

A. Pump Frequency Difference

As seen in the above experiments, the pump frequency difference should be carefully chosen in our conversion scheme.
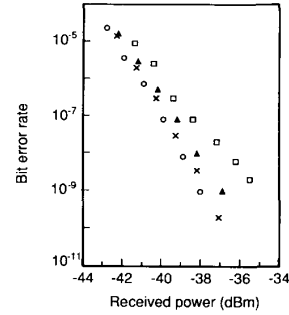

Fig. 5. Bit error rate for wavelength converted light. Pump frequency difference is set at 1.9 GHz (crosses), 1.4 GHz (triangles), and 1 GHz (squares). Circles are bit error rates for original signal light.

This section analytically discusses the effect of the frequency difference on system performance.

When the frequency difference is small, the beat frequency component in (7) is not completely eliminated by the baseband filter and interferes with the desired signal. The beat component level depends on the polarization state as shown in Fig. 3. The worst situation is a case where the signal light has an intermediate polarization state between those of the two pump lights such that $|A_{s1}| = |A_{s2}| = \sqrt{P_s/2}$. In this case, (7) is rewritten as

$$S = KP_s + KP_s \cos\phi \cos(2\pi\Delta ft) \qquad (9)$$

where

$$K = 2kP_0^2.$$

The worst case is considered in the following, using (9).

Here, we introduce the Gaussian approximation for discussing BER [12]. It is known that the Gaussian approximation is useful in considering the crosstalk influence in multichannel coherent systems [13], which is a similar situation to the present one. In the Gaussian approximation, BER is written as

$$\mathrm{BER} = \frac{1}{\sqrt{2\pi}} \int_Q^\infty \exp\left(-\frac{t^2}{2}\right) dt \qquad (10)$$

with

$$Q = \frac{S_m - S_s}{\sigma_m + \sigma_s} \qquad (11)$$

where S_m and σ_m are the mean level and the variance for mark signals, and S_s and σ_s are those for space signals, respectively. It is noted in (10) that BER is uniquely determined by a Q-value expressed by (11). For example, BER $= 10^{-9}$ for $Q = 6$.

For our situation expressed by (9), the parameters in (11) are written as

$$S_m = KP_s \qquad (12a)$$

$$S_s = 0 \qquad (12b)$$

$$\sigma_m^2 = \sigma_s^2 = N_0 + N_{\text{in}} \qquad (13)$$

where N_{in} is the interference noise power resulting from the second term in (9), and N_0 is the noise power other than

the interference noise. Since the amplitude of the interference noise is proportional to the signal light power P_s, as seen in (9), N_{in} is expressed by

$$N_{in} = c(KP_s)^2. \tag{14}$$

Here, c is proportional constant. On the other hand, we assume, for simplicity, that N_0 is independent of the signal light power.

By substituting (12a), (12b), (13), and (14) into (11), the signal light power, to achieve a certain BER, is obtained as

$$KP_s = \frac{2Q_0\sqrt{N_0}}{\sqrt{1 - 4Q_0^2 c}} \tag{15}$$

where Q_0 is the Q-value for a certain BER. Without the interference, i.e., $c = 0$, the signal light power, to achieve the same BER, is

$$KP_{s0} = 2Q_0\sqrt{N_0}. \tag{16}$$

The power penalty is obtained from (15) and (16) as

$$\begin{aligned}
(\text{power penalty})\text{dB} &= 10 \cdot \log\left[\frac{P_s}{P_{s0}}\right] \\
&= -5 \cdot \log\left[1 - 4cQ_0^2\right]. \tag{17}
\end{aligned}$$

In order to evaluate the power penalty, parameter c in (17) must be calculated, which can be carried out by estimating the interference noise power after the baseband filter, as shown below. Assuming that the baseband filter has a rectangular transmittance, the interference noise power is written as [14]

$$\begin{aligned}
N_{in} &= \int_{-B}^{B} G(f)df \\
&= \frac{(KP_s)^2}{32} \int_{-B}^{B} \left\{\delta(f - \Delta f) + T\text{sinc}^2[\pi(f - \Delta f)T]\right. \\
&\quad \left. + \delta(f + \Delta f) + T\text{sinc}^2[\pi(f + \Delta f)T]\right\}df \\
&= \frac{(KP_s)^2}{16} \int_0^B T\text{sinc}^2[\pi(f - \Delta f)T]df \tag{18}
\end{aligned}$$

where $G(f)$ is the power spectrum density of the beat component appearing in the second term in (9), $1/T$ is the data rate, and B is the filter bandwidth that is smaller than Δf. A comparison of (14) and (18) shows that

$$c = \frac{1}{16} \int_0^B T\text{sinc}^2[\pi(f - \Delta f)T]df. \tag{19}$$

By using (17) with (19), the power penalty can be evaluated. The result is shown in Fig. 6, where power penalty as a function of the normalized frequency difference Δf/(data rate) is plotted. The filter bandwidth is assumed to be equal to the data rate. It is indicated in Fig. 6 that a frequency difference three times as large as the data rate causes little degradation.

In the above treatment, the noise power, other than the interference noise, is assumed to be independent of the signal light power. A simple expression for the power penalty can be obtained using this assumption, as shown above. On the other hand, it is possible to include the shot noise power that is proportional to the signal light power. We also derived an expression for the power penalty, considering the shot noise,
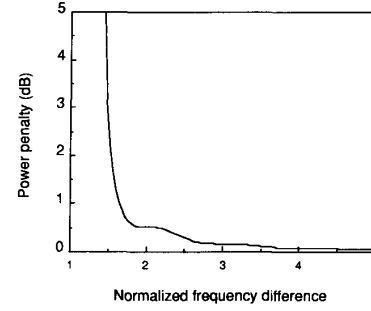

Fig. 6. Calculation for power penalty due to interference noise of beat component. Frequency difference is normalized as Δf/(data rate).

which appeared to be a complicated form, though it is not presented in this paper. A calculation example shows that taking the shot noise into account does not cause serious difference from the above treatment.

B. Efficiency

The efficiency of wavelength conversion is an important issue for practical applications. This section discusses the efficiency of the proposed conversion scheme and compares conventional wavelength conversion utilizing fiber FWM with polarization control [8]. Using the total pump power of $P_t = 2P_0$, (8) is rewritten as

$$S = \frac{1}{2}kP_t^2 P_s. \tag{20}$$

On the other hand, in the conventional polarization sensitive wavelength conversion, the detected signal of the converted light is

$$S = kP_t^2 P_s. \tag{21}$$

A comparison of (20) and (21) shows that the conversion efficiency in the proposed system is 3 dB less than that in the polarization sensitive scheme, provided that the total pump light power is the same. That is, the polarization insensitiveness is obtained at the expense of the efficiency. Note that the efficiency penalty due to polarization insensitiveness is 6 dB in the wavelength converter using fiber FWM with a looped configuration [9]. Thus, the present system is preferable to the previous polarization insensitive scheme from the viewpoint of efficiency.

However, the above discussion is not necessarily true for maximum conversion efficiency. As seen from (20) or (21), the conversion efficiency increases as the pump power increases. The maximum efficiency is determined by the available pump power, which is limited by stimulated Brillouin scattering (SBS) [15]. Beyond the SBS threshold, the pump power is not efficiently input into a fiber and the conversion efficiency is restricted.

The SBS threshold depends on the pump light configuration. Fig. 7 shows the SBS characteristics, where total pump power, at the fiber output as a function of that at the fiber input, is measured, for two pump configurations. One configuration, denoted by the squares, has a single pump light, and the other
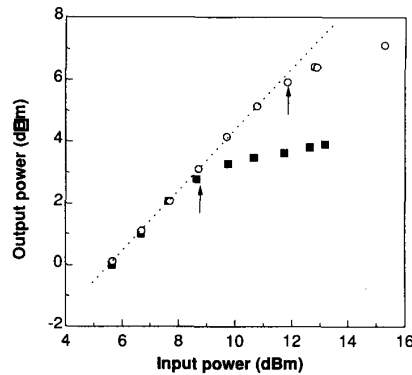
Fig. 7. Characteristics of stimulated Brillouin scattering in two pump configurations. Circles are for a two-orthogonal-pump configuration, and squares are for a single-pump configuration. 20 km dispersion-shifted fiber is used.

one, denoted by the circles, has two orthogonal pump lights with a frequency difference of 4 GHz. The pump light sources are DFB-LD's, and the fiber used in the measurement is a 20 km dispersion-shifted fiber that is the same one used in Section III. The input level where SBS starts is 3 dB larger in the polarization multiplexed system than that in the conventional one, as shown in Fig. 7. Thus, the available pump power in the proposed conversion scheme is 3 dB larger than that in the previous polarization sensitive conversion.

When the pump power increases by 3 dB, the conversion efficiency increases by 6 dB, as seen from (20) or (21). Taking the efficiency penalty for the polarization insensitiveness into account, which is discussed in the first part of this section, the maximum efficiency in the present system will be 3 dB higher than that in the conventional polarization sensitive conversion.

C. Disadvantage

At the final of the discussion section, a disadvantage of the proposed conversion is mentioned. That is, the converted light is not an accurate replica of the original light. The converted light diverses to three frequencies of $2f_p - f_s, 2(f_p + \Delta f) - f_s$, and $2f_p + \Delta f - f_s$, depending on the polarization state of the signal light. Therefore, if we try to sequentially convert a signal light, the frequency spectrum becomes broader and broader, which is not preferable in practice. Thus, the proposed scheme is not applied to multistage conversion systems.

V. SUMMARY

A novel polarization insensitive wavelength conversion was proposed and demonstrated. Fiber FWM was utilized with two orthogonal pump lights having different frequencies. Although the generation process of the converted light is sensitive to the polarization state, the baseband signal is independent of it in direct detection. In the experiments, the baseband signal of the converted light was observed constant within 0.5 dB

irrespective of the polarization state of the signal light, and the conversion operation was confirmed by measuring the BER.

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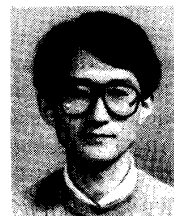
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