A novel modulation technique to enhance the optical intensity of referenced light for BOTDR's high-accuracy signal interrogation

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Heterodyne coherent detection is an optimal technique for Brillouin optical time domain reflectometer (BOTDR) on account of high resolution and good accuracy. Referenced light with enhanced intensity and with Brillouin frequency shift is important for BOTDR's signal interrogation. A novel modulation technique, combining the regulating the DC bias voltage of electro-optic intensity modulator (EOIM) and the polarization state of the incident light, is proposed. Polarization influence on the intensity of sidebands generated by EOIM is investigated theoretically and experimentally. It is found that intensity of sideband change with the polarization state according to a $\cos^2 x$ relationship. Referenced light's intensity can be enhanced further by adjusting the polarization state of the incident light after the action of DC voltage regulation has been exhausted. The intensity difference of 1st-order sideband and 0-order scattering (Rayleigh scattering), I_1-I_0, reaches maximum when polarization angle is 63.7^{O} and the bias point of the EOIM is set in the nonlinear response range near the bottom. I_1-I_0 is 18dB higher than that of merely regulating DC bias voltage. Higher extinction ration (ER) of EOIM, higher I_1-I_0 can be achieved. When I_1-I_0 reaches maximum, the intensity difference between 1st-order sideband and other sidebands all reach maximum too. Meanwhile, the 1st-order sideband is best for being as referenced light for BOTDR's signal interrogation.

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Keyword: BOTDR, Signal interrogation, Modulation technique, Referenced light, Polarization

1. Introduction

Distributed Brillouin optical fiber sensor applied in long distance distributed real-time monitoring has drawn considerable attention due to its advantage of one-end access and long sensing distance [1-4]. At present, Brillouin optical time domain reflectometer (BOTDR) becomes one of the leading edge technologies investigated all over the world for high resolution temperature and strain measurement [5-7]. The key to the BOTDR system is signal detection as the spontaneous Brillouin scattering is rather weak. With the merit of high sensitivity and signal-to-noise (SNR) improvement, heterodyne coherent detection is usually applied to BOTDR to detect weak Brillouin scattering signal [8-10]. The focus is how to acquire optimal referenced light. Electro-Optic Intensity Modulator (EOIM) can generate sidebands conveniently. The two 1st-order sidebands are commonly used for referenced light for heterodyne coherent detection in a BOTDR [11-12].

There have also 0-order sideband and many other higher-order sidebands of the output light from EOIM besides the two 1st-order sidebands when microwave signal loaded on an EOIM. But, the 0-order sideband and higher-order sidebands are not only useless for Brillouin sensor's interrogation, but also bring background noise to system. Especially, the intensity of 0-order sideband should be reduced thoroughly as far as possible to concentrate energy to 1st-order sidebands. Increasing the optical intensity difference between 1st-order and 0-order ($I_1 - I_0$) to improve the interrogation accuracy of the system. At present, regulating DC voltage loaded on EOIM to make intensity of 1st-order sidebands higher than other sidebands (especially 0-order sideband) is the common method [13]. However, the referenced light acquired by means of only regulating DC voltage has two disadvantages. The first one is that the signal is unstable and sensitive to polarization state of incident light, which can be solved by polarization controller [14-15]. The other one is that the intensity difference between 1st-order sidebands and other sidebands is not large enough. Choosing EOIM with higher extinction ratio (ER) can solve the problem, but the cost increases too. However, there are few reports about the research on how polarization influence on the intensity of sidebands generated by EOIM and increasing $I_1 - I_0$ by polarization state of the incident light to generate high intensity referenced light for BOTDR's signal interrogation. This paper proposes a new method combined regulating DC bias voltage of EOIM and polarization state control to generate high intensity referenced light. Results show that polarization not only can stabilize the intensity of sidebands generated by EOIM but also increase $I_1 - I_0$. Stable referenced light with greater $I_1 - I_0$, which is of benefit to interrogation, has been achieved by theoretically investigation and experimentally demonstration.

2. Principle

The structure diagram and optical path diagram of EOIM are shown as Fig. 1:

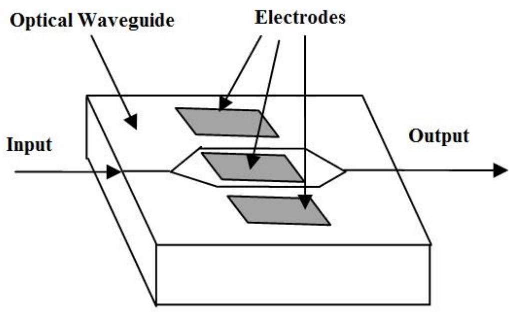


Fig. 1. (a) The structure of EOIM.

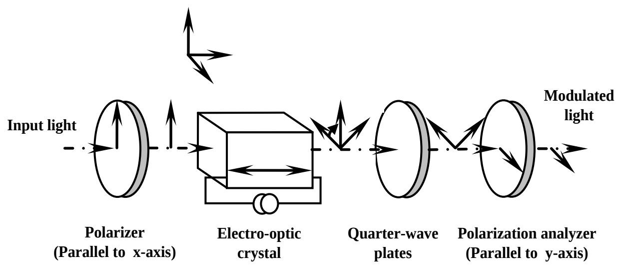


Fig. 1. (b) The optical pathway diagram of EOIM.

The optical wave output from Mach-Zehnder interferometer is:

$$E = E_0 \cos(\omega_0 t)\cos[C\cos(\omega_m t) + \varphi_{DC}] \quad (1)$$

Where C is the modulation depth, and is φ_{DC} the phase caused by the DC bias voltage. E_0 and ω_0 are the amplitude and angular frequency of the input light and ω_m is the angular frequency of microwave signal, respectively [13].

Suppose the polarization angle of incident light of EOIM is x, then input optical wave of electro-optical crystal is:

$$E = E_0 \cos x \cos(\omega_0 t)\cos[C\cos(\omega_m t) + \varphi_{DC}] \quad (2)$$

According to the Bessel function expansions of first kind, Eq. (2) can be expanded as:

$$E = E_0 \cos x \cos(\omega_0 t)\left\{\begin{array}{l}\left[J_0(C) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(C)\cos(2n\omega_m t)\right]\cos\varphi_{DC} \\ -\left\{2\sum_{n=0}^{\infty}(-1)^n J_{2n+1}(C)\cos\left[(2n+1)\omega_m t\right]\right\}\sin\varphi_{DC}\end{array}\right\} \quad (3)$$

Then optical intensity of 0~3 order sidebands can be expressed as:

0-order:

$$E_0^2\cos^2 x J_0^2(C)\cos^2\varphi_{DC} = \frac{1}{2}E_0^2\cos^2 x J_0^2(C)[1+\cos(2\varphi_{DC})] \quad (4a)$$

1-order:

$$E_0^2\cos^2 x J_1^2(C)\sin^2\varphi_{DC} = \frac{1}{2}E_0^2\cos^2 x J_1^2(C)[1-\cos(2\varphi_{DC})] \quad (4b)$$

2-order:

$$E_0^2\cos^2 x J_2^2(C)\cos^2\varphi_{DC} = \frac{1}{2}E_0^2\cos^2 x J_2^2(C)[1+\cos(2\varphi_{DC})] \quad (4c)$$

3-order:

$$E_0^2\cos^2 x J_3^2(C)\sin^2\varphi_{DC} = \frac{1}{2}E_0^2\cos^2 x J_3^2(C)[1-\cos(2\varphi_{DC})] \quad (4d)$$

According to Eq. (4), the optical intensity of sidebands depend on E_0, x, C , as well as ϕ_{DC}.

The optical intensity difference between 1-order and 0-order is:

$$I_1 - I_0 = \frac{1}{2}E_0^2\cos^2 x\left\{J_1^2(C)\left[1-\cos(2\varphi_{DC})\right] - J_0^2(C)\left[1+\cos(2\varphi_{DC})\right]\right\} \quad (5)$$

E_0, $J_0(C)$, $J_1(C)$, $\cos\phi_{DC}$ are fixed when optical source, EOIM, microwave and DC voltage are maintained the same. It is supposed that:

$$\frac{1}{2}E_0^2 J_n^2(C)[1+\cos(2\varphi_{DC})] = k_n, (n = 2k, k = 0,1,2......) \quad (6a)$$

$$\frac{1}{2}E_0^2 J_n^2(C)[1-\cos(2\varphi_{DC})] = k_n, (n = 2k+1, k = 0,1,2......) \quad (6b)$$

And then, Eq. (4) can be simplified as:

0-order:

$$I_0 = E_0^2 \cos^2 x J_0^2(C) \cos^2 \phi_{DC} = k_0 \cos^2 x \tag{7a}$$

1-order: $$I_1 = E_0^2 \cos^2 x J_1^2(C) \sin^2 \phi_{DC} = k_1 \cos^2 x \tag{7b}$$

2-order: $$I_2 = E_0^2 \cos^2 x J_2^2(C) \cos^2 \varphi_{DC} = k_2 \cos^2 x \tag{7c}$$

3-order: $$I_3 = E_0^2 \cos^2 x J_3^2(C) \sin^2 \varphi_{DC} = k_3 \cos^2 x \tag{7d}$$

And Eq. (8) can be deduced as:

$$I_1 - I_0 = (k_1 - k_0)\cos^2 x \tag{8}$$

From Eq. (7), it is clear that intensity of 0 to 3 order sidebands change with $\cos^2 x$ when optical source, EOIM, microwave and DC voltage keep unaltered, while regulate polarization controller (PC) to change x. Not all of sidebands' intensity changes with x at the uniform speed because of the difference value of $k_n, (n = 0,1,2......)$ induced by difference value of $J_n(C), (n = 0,1,2......)$ according to Fig.2. Bigger the value of $k_n, (n = 0,1,2......)$ is, faster the intensity of n-order sidebands change with x. Theoretically, E_0 keeps constant when x changes. However, E_0 is uneven in fact causing $k_n, (n = 0,1,2......)$ unevenly, as K shown in Fig.3. So that sidebands' intensity is not change $\cos^2 x$ times with x strictly , as $K(\cos x)^2$ shown in Fig. 3.

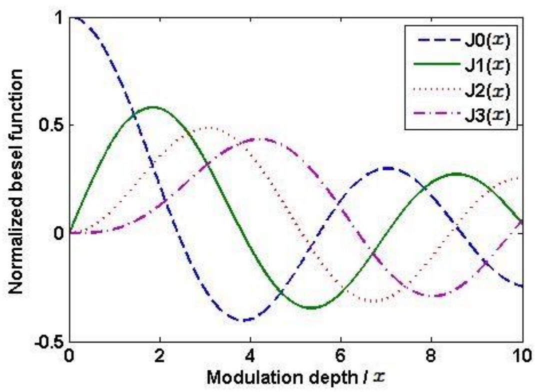


Fig. 2. Curve of $J_0(x)$, $J_1(x)$, $J_2(x)$, and $J_3(x)$

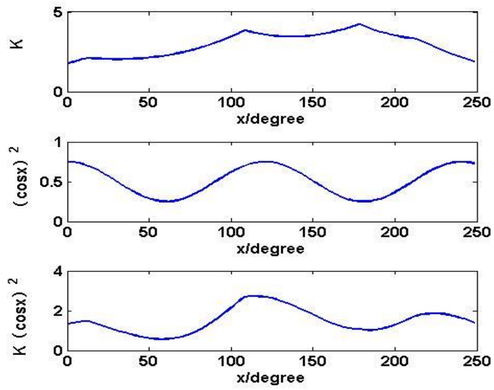


Fig. 3. The simulation of sidebands' intensity changing with x.

3. Experimental setup

A DFB laser with the center wavelength of 1550.12nm is used as optical source, as shown in Fig.4. The DFB laser has a narrow linewidth of 5 kHz and a low frequency drift of 5MHz. A fiber squeezer polarization controller controls polarization state of the incident light of 10Gbit/s $LiNbO_3$ EOIM with 28dB extinction ration (ER). Regulating microwave source and DC bias voltage loaded on the EOIM, wavelength shift (corresponding to frequency shift) can be observed in the optical spectrum analyzer (OSA). The OSA is YOKOGAWA AQ6370 and has a measurement wavelength range of 600nm~1700nm and a wavelength accuracy of 0.02nm. There are optical frequencies like $\omega_0 \pm \omega_m$, $\omega_0 \pm 2\omega_m$, $\omega_0 \pm 3\omega_m$, $\omega_0 \pm n\omega_m$, besides ω_0 ------the frequency of incident light. Interval of sideband depends on ω_m. When ω_m equal to Brillouin frequency shift, the 1st-order sideband can be used as referenced light for signal interrogation. The peak intensity of sidebands can be further adjusted when changing amplitude of microwave, polarization states of incident light of EOIM and DC voltage, and then a stable referenced light with high $I_1 - I_0$ can be achieved.

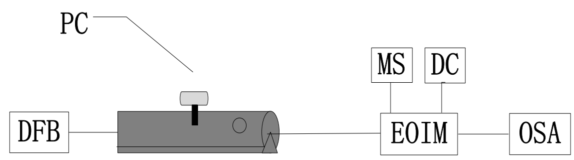


Fig. 4. Schematic diagram of experimental setup.

DFB: Distributed Feed Back laser
PC: Polarization controller
MS: Microwave Source
DC: DC supply
EOIM: Electro-Optic Intensity Modulator
OSA: Optical Spectrum Analyzer

4. Results and discussion

The transmission curve of the EOIM is shown in Fig. 5, when only regulating DC bias voltage and without RF modulation signal.

The output optical spectrum of the modulated EOIM is shown in Fig. 6, measured with the RF modulation of 11 GHz and 26 dBm and DC bias voltage of 4.55 V, 7.44V and 6.89V, respectively, namely the bias point is set in the linear, bottom and nonlinear response range, respectively. And the variation curve of intensity of 0 to 3 order sidebands is shown in Fig. 7 when PC is regulated within a circle round in the three response range.

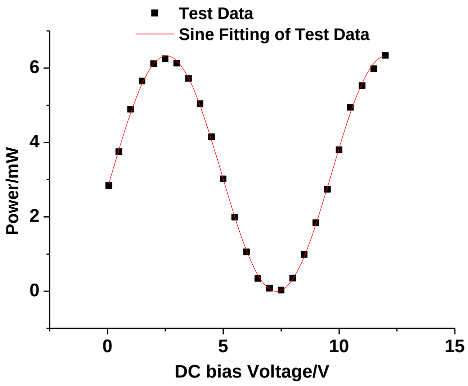
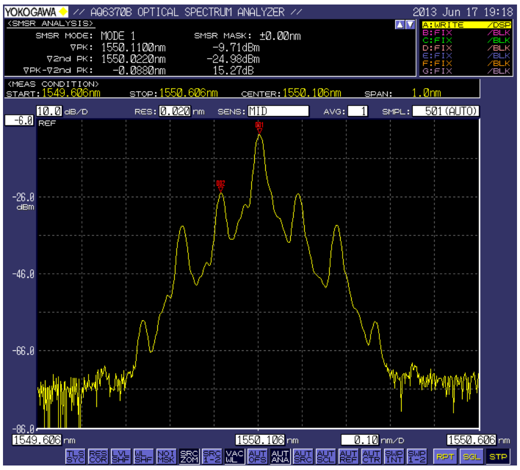
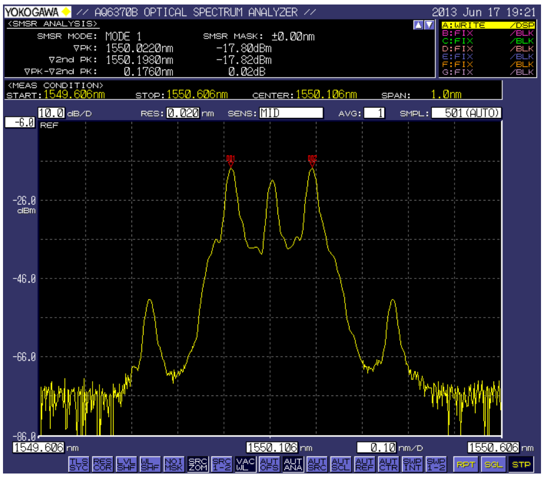


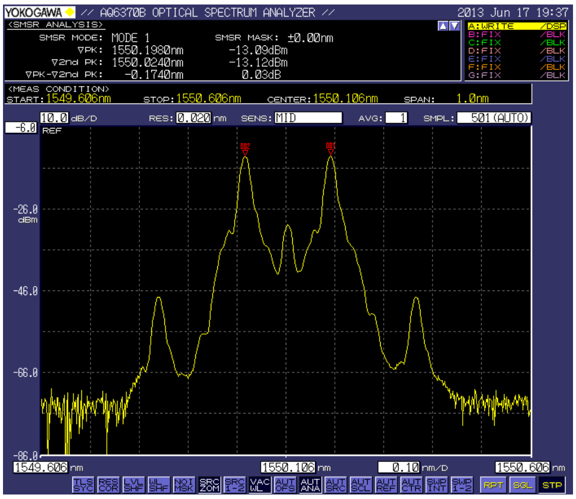
Fig. 5. Transmission curve of EOIM.



(a) Linear response range

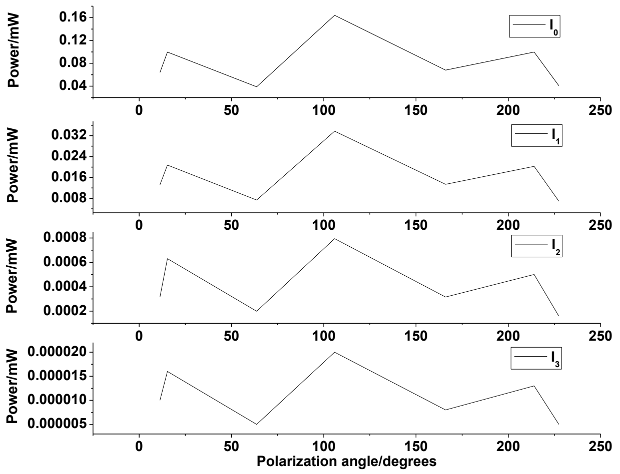


(b) *Bottom response range*

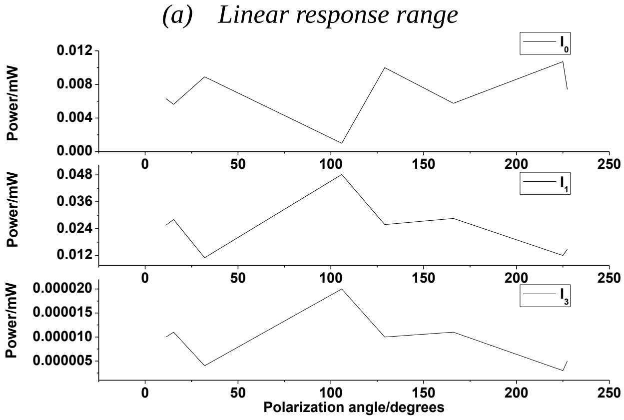


(c) Nonlinear response range

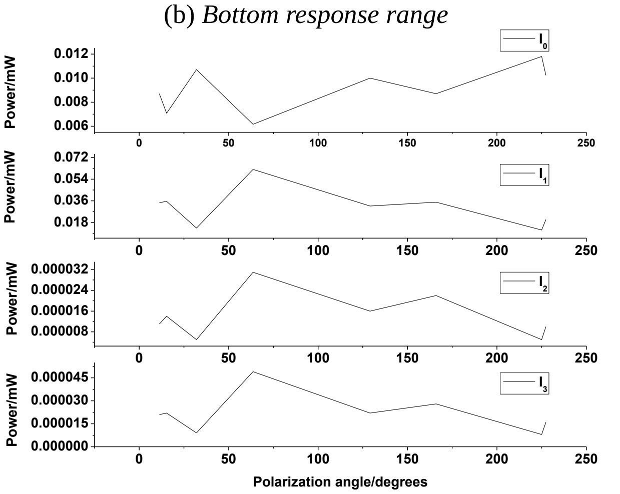
Fig. 6. Spectrum of output of EOIM when the bias point is set in: (a) linear response range, (b) bottom response range, (c) nonlinear response range.



(a) *Linear response range*



(b) *Bottom response range*



(c) *Nonlinear response range*

Fig. 7. The variation curve of the optical intensity of 0~3 order sidebands when regulate PC a circle round basing on the bias point is set in the: (a) linear response range, (b) bottom response range, (c) nonlinear response range.

Light leakage of EOIM is unavoidable, and the wavelength of leakage light is mainly located at λ_0, the wavelength of optical source. Therefore, the optical intensity at λ_0 is $I_0 = I_{00} + I_{cw}$, where I_{00} is the intensity of 0-order sideband, and I_{cw} is caused by leakage light. The relationship of I_{cw} and the EOIM's ER is:

$$ER = 10\log\frac{I + I_{cw}}{I_{cw}} \tag{9}$$

Where I consists of optical intensity of all the sidebands generated by EOIM. From Fig. 8, it is obvious that I_{cw} decreases with the increase of ER, and only when $ER \to +\infty$, I_{cw} turns to 0.

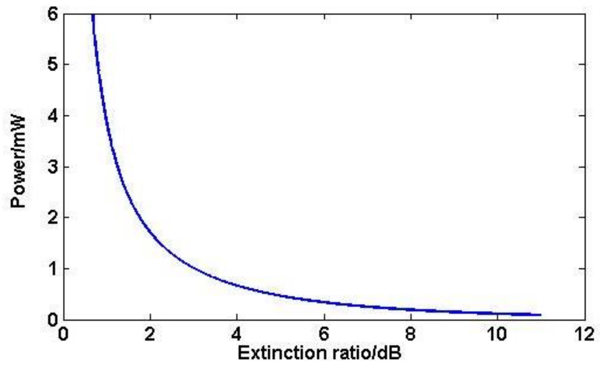


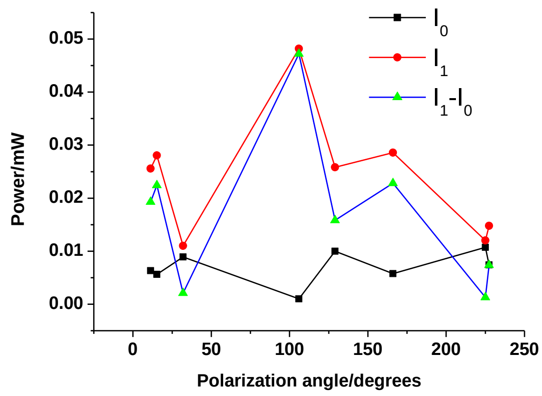
Fig. 8. The relationship curve between I_{cw} *and ER of EOIM.*

$\varphi_{DC} = \frac{\pi}{4}$ and $\sin^2\varphi_{DC} = \cos^2\varphi_{DC} = \frac{1}{2}$ will be appropriated when the bias point of the EOIM is set in the linear response range. From Fig. 6 (a), it is obvious that both odd and even order sidebands are bigger, and the difference of sidebands' intensity is mainly caused by difference of $J_n(C)$ according to Eq. (4). The ratio of odd order sidebands' intensity and even order sidebands' intensity is expressed as $\frac{I_{2n}}{I_{2n+1}} = \frac{J_{2n}(C)}{J_{2n+1}(C)}$ and then C=0.811 is easy to get. I_0 is consisted mainy of I_{00}, as the intensity of 0-order is higher in this condition. All the sidebands have different intensity, but have the same change trend when PC is adjusted a circle round based on that the bias point is set in the linear response range, as shown in Fig.7 (a). The intensity change tendency agrees well with the third simulation curve shown in Fig.3.

$\varphi_{DC} = \frac{\pi}{2}$, and $\sin^2\varphi_{DC} = 1, \cos^2\varphi_{DC} = 0$ will be appropriated when the bias point of EOIM is set in the bottom response range. Theoretically, all the intensity of even order sidebands should be 0 in this situation. From Fig.6 (b), it is evident that 2nd-order sidebands are disappeared. However, I_0 is still big because it is composed mainly of I_{cw}. I in Eq.(9) predominantly be intensity of odd order sidebands since all the intensity of even order sidebands almost be 0. ER increase and I_{cw} decrease when intensity of odd order sidebands are increasing because of polarization change, and the result is I_0 decrease, and vice versa. 1st-order and 3rd-order sidebands have the same variation tendency when regulate PC a circle round basing on the bias point is set in the bottom response range, as shown in Fig. 7 (b).

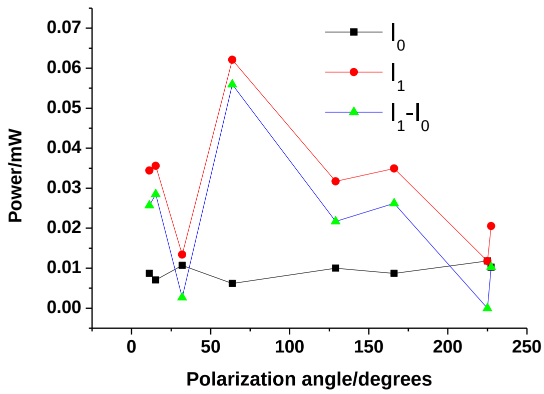
The DC bias voltage is 6.89V, so the EOIM is set in the nonlinear response range near the bottom. Then $\varphi_{DC} \to \frac{\pi}{2}$, $\sin^2 \varphi_{DC} \to 1, \cos^2 \varphi_{DC} \to 0$, $I_{00} \to 0$, and I_0 is mainly I_{cw}. 1 to 3 order sidebands have the same variation tendency when PC is regulated a circle round basing on the bias point is set in the nonlinear response range near the bottom, as shown in Fig.7(c). If the DC bias voltage of EOIM is set in the nonlinear response range near the linear response range, then I_0 is mainly I_{00}, and Fig. 7(c) will similar to Fig. 7 (a).

The 1-order sideband is commonly used as referenced light for heterodyne coherent detection in a BOTDR. The demand is to concentrate energy to 1-order sideband and therefore increase the accuracy of interrogation. How to weaken I_0 and enhance $I_1 - I_0$ as much as possible is the key. $I_0 > I_1$ becomes easily when $\varphi_{DC} < \frac{\pi}{4}$ and $\sin^2 \varphi_{DC} > \cos^2 \varphi_{DC}$, therefore only the nonlinear response range near the bottom and the bottom response range should be taken into account. In these area, the intensity of even order sidebands nearly be 0, and can be smaller by suitable polarization setting. Fig.9 is the variation chart of I_0, I_1 and $I_1 - I_0$ when regulate PC a circle round basing on the bias point is set in the nonlinear response range near the bottom and the bottom response range. From Fig.9 (a) we can see that $I_1 - I_0$ reaches 0.048mW, the maximum, when the polarization angle is 105.9° basing on the bias point is set in the bottom response range. From Fig.9 (b) we can see that $I_1 - I_0$ reaches 0.057mW, the maximum, when the polarization angle is 63.7° basing on the bias point is set in the nonlinear response range near the bottom. When $I_1 - I_0$ reaches maximum, the optical intensity difference between 1-order sidebands and other sidebands reaches maximum too. In other word, the two 1-order sidebands are best for the referenced light for heterodyne coherent detection in a BOTDR, when polarization angle is 63.7° and the bias point of the EOIM is set in the nonlinear response range near the bottom.



(a) *Bottom response range*

(b)

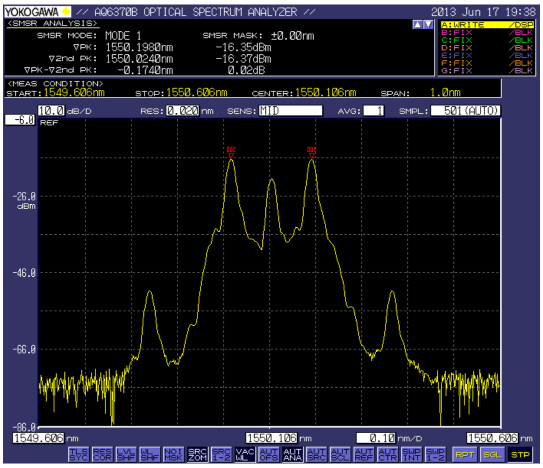


(b) Nonlinear response range.

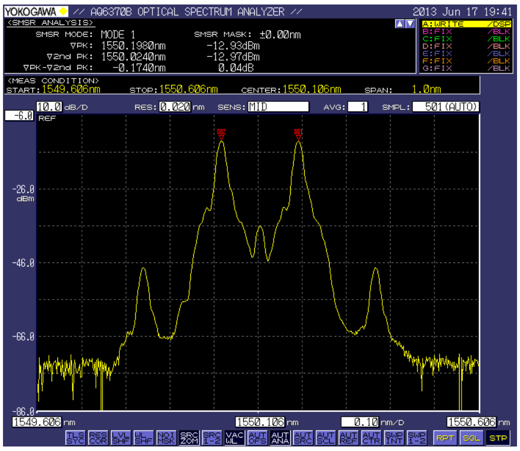
Fig. 9. (a) The variation chart of I_0, I_1 and $I_1 - I_0$ when PC is adjusted a circle round based on that the bias point is set in: (a) the bottom response range, (b) the nonlinear response range near the bottom.

After setting microwave signal, only regulate DC voltage to make $I_1 - I_0$ reaches maximum. When $I_1 - I_0$ can't be bigger any more, $I_1 - I_0$ is about 6 dB, as shown in Fig.10 (a). Basing on this, regulating PC can increase $I_1 - I_0$ reaches 24dB, as shown in Fig.10 (b). Thanks to polarization, $I_1 - I_0$ is 18dB higher than that of just regulating DC bias voltage.

Upper $I_1 - I_0$ will gain if the ER of EOIM is higher. Moreover, $I_1 - I_0$ can keep stable at maximum for a longer time due to that PC is used in the system. This is pretty important for detecting the weak Brillouin scattering signal.



(a)



(b)

Fig. 10.(a) The spectrum of maximum $I_1 - I_0$ *achieved by: (a) only adjusting DC voltage, (b) adjusting PC with the adjusted DC voltage.*

5. Conclusion

A novel modulation technique combining the regulating DC bias voltage of EOIM and the polarization state of the incident light is proposed to enhance the intensity of the referenced light for BOTDR's high-accuracy signal interrogation. The polarization state influence on the intensity of sidebands generated by EOIM is investigated theoretically and demonstrated experimentally. Experimental results have been explained in detail when the bias point is set in the linear, bottom and nonlinear response range, respectively. It is found that intensity of sidebands change with polarization according to a $\cos^2 x$ function relationship.

Referenced light's intensity can be enhanced greatly by optimizing and then controlling the polarization state of incident light of the EOIM, after the action of DC voltage regulation has been exhausted. $I_1 - I_0$ reaches maximum when polarization angle is 63.7^O and the bias point of the EOIM is set in the nonlinear response range near the bottom. Attribution to polarization, $I_1 - I_0$ is 18dB higher than that of solely regulating DC bias voltage. Higher ER of EOIM, higher $I_1 - I_0$ can be obtained. When $I_1 - I_0$ accomplishes maximum too, the optical intensity difference between 1-order sideband and other sidebands reaches maximum too, and the 1st-order sideband is best for the referenced light for BOTDR's high-accuracy signal interrogation. This finding may have important implications for high resolution distributed Brillouin optical fiber sensor applied in long distance distributed real-time monitoring.

Acknowledgments

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