Polarization properties in a prism laser gyro with mechanical dither bias*

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Theoretical analysis and experimental research on the polarization properties of output light in gyro are carried out to investigate the phenomenon that the amplitude of an output voltage signal is modulated by dither bias in laser gyros consisting of totally reflecting prisms. Taking the effect of prism stress birefringence into account, an analytical formula of the output light intensity in the gyro and the relationship between the polarization parameter and the amplitude modulation of the output signal are obtained and discussed. For the first time, the polarized power value of the output light is adopted as a basis to estimate the output signal amplitude fading extent of laser gyros. Experimental results demonstrate that when the value of polarized power of output light is below 25.5% of that in ideal static case, the standard error is over 0.0337 dBm, and the displacement extent of the prism is higher than 53% of the radius of the beam waist in the gyro cavity, the amplitude modulation extent of gyro output signal can reach up to 16%, which badly influences the measurement accuracy of the laser gyro. Using this polarized power detecting measurement method can repair the gyro immediately during its fabrication process, improve the testing and production efficiency and shorten the product development cycle.

Keywords: prisms laser gyro, mechanical dither, stress induced birefringence, polarized detection

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1. Introduction

As a new type of optical inertial device widely used in navigation, aeronautics, and space engineering, prisms laser gyro processes many advantages such as a quick starting, simple craft, stable performance, and high ability to prevent interference.[1−3] In order to keep the gyro working status out of lock-in, mechanical dither is usually adopted to improve gyro performance.[4,5] In engineering practical use, it is found that the amplitude of an output voltage signal of a prism laser gyro is always modulated by dither bias, which badly influences the measurement accuracy of the gyro.[6,7] Recently, signal process technology and output coupled light detection for prism laser gyros have been studied. In 2008, Wan *el al.*[8] indicated that the mechanical dither of biasing system brings an alternating force to the optical devices in a laser gyro, and thus makes the output light intensity modulated with the same frequency as that of dither biasing. In 2011, Min[9] used synchronization theory to control two chaotic gyros with nonlinear damping for the asymptotic unstable output signal. Zhang *el al.*[10] believed that the turntable angular position errors induced during the dithered biasing could cause unexpected error in gyros according to the experimental results. Currently, the performance test mainly refers to the fabricated laser gyro. Any gyro that cannot meet the requirements needs to be disassembled for repair. Assembly error and unevenly distributed prestressing force are the important reason for the intensity modulation phenomenon of output light. The larger the assembly error of prisms, the greater the extent of output light intensity modulation will be. This influence reflected in the polarization characteristic of output light appears as the lower value of light power. Analysis shows that output light power mean value in dither bias is generally less than that of a static case, while the standard deviation value is larger than that of the static case. Therefore, by testing the polarization characteristic of output light, the extent of intensity modulation can be predicted before the gyro assembly is crafted, and the unqualified parts could be repaired in time, thereby avoiding restoration of the fabricated laser gyro, the efficiency of gyro test and production would increase conspicuously, and the product development cycle and cost can be reduced greatly.

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In this paper we perform theoretical analysis and experimental research on the polarization properties of output light in a gyro. A new basis based on power value of output polarized light to estimate the output signal amplitude fading extent of laser gyros is adopted for the first time, which is compared with the simulation results. As for the gyro, the driving voltage in this paper is 12 V. Experimental results demonstrate that when the value of output polarized light power is below the 25.5% of that in ideal static case, the standard error is over 0.0337 dBm, and the displacement extent of prism is higher than 53% of radius of the beam waist in gyro cavity, the amplitude modulation extent of the gyro output signal reaches up to 16%, which badly influences the measurement accuracy of the laser gyro. Owing to the fact that the test for gyro polarized light power can be done the moment prisms have been assembled, the criterion of prism assembly could be set according to these test methods, reducing the restoration operation of fabricated laser gyros. This test method based on polarized detection would provide an important reference for improving the quality of output light and the reliability of prism laser gyros.

2. Theoretical model

The geometrical structure model the of prism laser gyro used in this paper is shown in Fig. 1. The refractive indexes of these prisms are all 1.45738. Prism 4 is used to guild the dual light beams out of resonator so that they can interfere on the photodetector. The prisms at the top, numbered as 3, are used to make the light beam propagate as a ring trajectory. The He–Ne gas sealed in a capillary space with vacuum tube technology by two prisms numbered as 2, which keeps the laser medium free of contamination to provide a 0.6328-μm laser.[11]

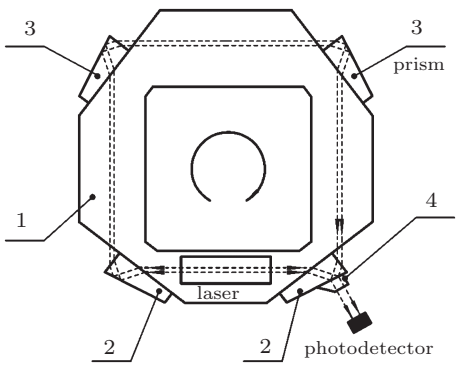


Fig. 1. Geometrical structure model of the prism laser gyro.

When the gyro is placed on the dither bias platform, the clockwise (CW) and counterclockwise (CCW) light beams, each of which has a wavelength of λ, will produce beat frequency $\Delta\upsilon$ owing to vibration. The output light, which has a fundamental Gaussian mode, is coupled on the photodetector through the combiner prism.[12] Let the photodetector surface be the XOY plane, then the light intensity can be calculated as follows:[13,14]

$$\begin{aligned} I(x,t) &= 2I_0 \cos^2\left(\pi\Delta\upsilon - \frac{\pi x\beta}{\lambda}\right) \\ &= \left(\sum_{i=1}^{2}\sqrt{\frac{\varepsilon}{\mu}}\,|E_i|^2 + \frac{\varepsilon}{\mu_0}\cos\theta\cos\varphi\cdot\prod_{i=1}^{2}|E_i|\right) \\ &\quad\times\ \cos^2\left(\pi\Delta\upsilon - \frac{\pi x\beta}{\lambda}\right), \end{aligned} \tag{1}$$

where I_0 and β are the intensity of interfered light beam and the angle between the output beams, respectively. ε and μ_0 are the permittivity and magnetic constant of the material respectively. θ is the angle between the two light beams interfered on the prisms, while φ is the phase difference between the two light beams, and E_i is the electrical field intensity of the light beam. Let the direction of light propagating be the z axis, and then the distribution of the electrical field on the photodetector could be depicted as follows:

$$\begin{aligned} E(x,y,z) &= \frac{a_0}{\omega^2(z)}\times\exp\left[-\frac{r^2}{\omega^2(z)}\right] \\ &\quad\times\ \exp \mathrm{i}\left[k\left(\frac{r^2}{2R(z)}+z\right)+\varphi(z)\right], \end{aligned} \tag{2}$$

where a_0 is the amplitude of the electrical field, $\omega(z)$ is the radius of the Gaussian light spot at z, $R(z)$ is the curvature radius of the phase plane in z for the Gaussian light.

For the reason that the output signal comes from the interference light coupled from the two laser beams in the gyro on the combiner prism, any factor that could make inner polarized light intensity change would influence the output light intensity for a practical gyro. The incident angle is no longer the Brewster angle, owing to birefringence in prisms, caused by mechanical dither bias. As a result, the intensity of the output polarized light of a prism laser gyro is always modulated by dither bias at the same frequency.[15,16] Figure 2 shows the output voltage signal curve of a practical gyro during two dither periods. Points T_1 and T_2 represent the moment of the velocity of gyro being zero, and the modulation depth (MD) of the prism laser gyro in Fig. 2 is defined as the difference in

count between the longitudinal coordinates of points V_1 and V_2.

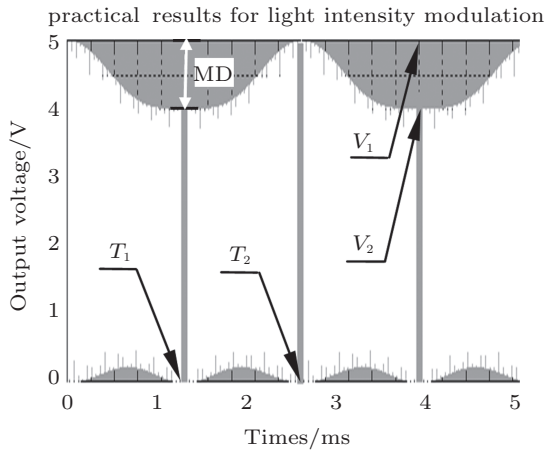


Fig. 2. Voltage signal curve of a practical gyro.

Figure 3 shows the propagating trajectory of light in each prism, where W represents the intensity of light.

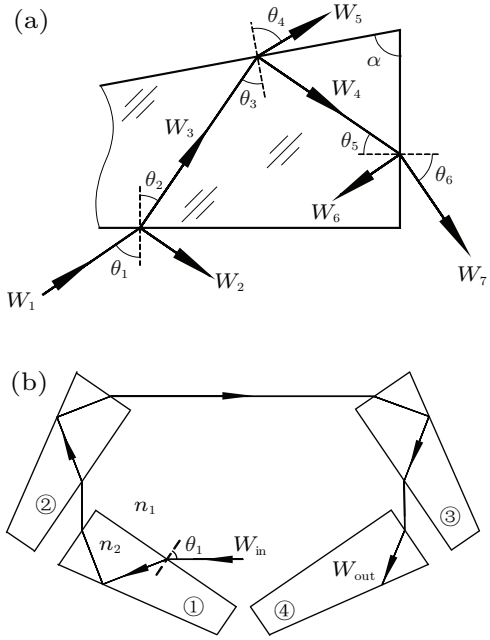


Fig. 3. Schematic diagram of a laser beam propagating through a prism: (a) light propagating through a single prism; (b) propagation situation for the whole cavity model.

According to the Fresnel equation, the W_3 can be obtained as follows:

$$W_{3\mathrm{p}} = \frac{\sin 2\theta_1 \cdot \sin 2\theta_2}{\sin^2(\theta_1+\theta_2)\cdot\cos^2(\theta_1-\theta_2)},$$
$$W_{3\mathrm{s}} = \frac{\sin 2\theta_1 \cdot \sin 2\theta_2}{\sin^2(\theta_1+\theta_2)}, \tag{3}$$

where θ_1 and θ_2 represent incidence angle and refraction angle, respectively.

Figure 3(a) shows that the light beam is reflected 3 times in one prism. All angles described in Fig. 3(a) can be calculated using Eq. (3) as follows:

$$\theta_2 = \arcsin\left(\frac{n_1}{n_2}\sin\theta_1\right),$$
$$\theta_3 = \frac{\pi}{2} - (\alpha - \theta_2),$$
$$\theta_5 = \alpha - \theta_3,$$
$$\theta_6 = \arcsin\left(\frac{n_2}{n_1}\sin\theta_5\right). \tag{4}$$

The whole light path analysis diagram is depicted in Fig. 3(b), which is not depicted in proportion. The initial incidence light angle θ_1 is assumed to be a constant value as designed, which equals the Brewster angle of the prism material. By using Eqs. (3) and (4) in each prism, the output light intensity W_{out} can be obtained.

In this paper we use a polarization ellipse to analyse the light characteristics. Figure 4 shows the typical result that the polarization measurement equipment obtains.

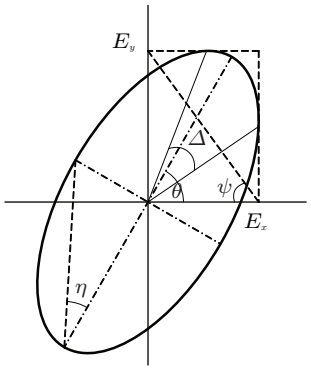


Fig. 4. Polarization ellipse and parameter definition diagram of output light.

In Fig. 4 θ and η represent the azimuthal angle and ellipticity for the ellipse, while other parameters could be calculated from these two data. In this paper we use PAT9000B modular polarization measurement equipment to survey the output light parameters, including azimuth θ, ellipticity η, delta Δ, Stokes parameters S_1, S_2, S_3, degree of polarization (DOP), power split ratio (PSR), and polarized power. The delta PSR and ψ shown in Fig. 4 are defined as follows:

$$\Delta = \tan^{-1}\left(\frac{E_y}{X_t}\right) - \tan^{-1}\left(\frac{Y_r}{E_x}\right),$$
$$\psi = \tan^{-1}\left(\frac{E_y}{E_x}\right),$$

$$\mathrm{PSR} = \cos^2 \psi, \tag{5}$$

where X_t and Y_r represent the horizontal and vertical coordinates of the E_x and E_y points.

Ideally, there is only P-polarized light propagating in gyro because of the refraction angle designed as the Brewster angle of the prism material. However, owing to birefringence in prisms in the dither bias case, the practical refraction angle cannot remain as the Brewster angle, and as a result there is little S-polarized light in the gyro. Therefore, strictly speaking, the light propagating in a gyro is elliptically polarized light in the case of dithered bias. To simplify the theoretical analysis, this elliptically polarized light can be regarded as a combination of two linearly polarized beams in any vertical direction.[17] Let the light propagate along the Z axis and the surface perpendicular to the Z axis be XOY plane, then the electric field intensities of these two linear polarized beams will be depicted as follows:[18]

$$\begin{aligned} E_x &= E_{ox} \cos(kz - \omega t), \\ E_y &= E_{oy} \cos(kz - \omega t + \delta), \end{aligned} \tag{6}$$

where E_{ox} and E_{oy} represent the amplitudes of electric field intensity of each direction respectively, $\boldsymbol{k}$ is the wave vector of light, ω is the light frequency, and δ is the phase difference.

Eliminating the time parameter t in Eq. (6), the elliptical path equation for endpoint of light vector moving in the XOY plane can be depicted as follows:

$$\left(\frac{E_X}{E_{ox}}\right)^2 + \left(\frac{E_Y}{E_{oy}}\right)^2 - 2\left(\frac{E_X}{E_{ox}}\right)\left(\frac{E_Y}{E_{oy}}\right)\cos\delta = \sin^2\delta. \tag{7}$$

According to Eq. (7), the intensity of the elliptically polarized light in a gyro can be calculated as[19]

$$\begin{aligned} I &= \frac{1}{2}\left(E_{ox}^2 + E_{oy}^2 + \sqrt{E_{ox}^4 + 2E_{ox}^2E_{oy}^2\cos 2\delta + E_{oy}^4}\right) \\ &\quad + \frac{1}{2}(E_{ox}^2 + E_{oy}^2 \\ &\quad - \sqrt{E_{ox}^4 + 2E_{ox}^2E_{oy}^2\cos 2\delta + E_{oy}^4}) \\ &= E_{ox}^2 + E_{oy}^2. \end{aligned} \tag{8}$$

Moreover, the light intensity can be calculated by the Stockes parameters, which can be obtained for the output light shown in Fig. 4 as follows:

$$\begin{aligned} S_0 &= E_{ox}^2 + E_{oy}^2, \\ S_1 &= E_{ox}^2 - E_{oy}^2, \\ S_2 &= 2E_xE_y\cos\Delta, \\ S_3 &= 2E_xE_y\sin\Delta. \end{aligned} \tag{9}$$

3. Experiment and discussion

3.1. Simulation analysis for output light intensity

For the gyro structure shown in Fig. 1, the prism stress can increase with dithered palstance and amplitude increasing, thus making the refraction index changed and light off axis, thereby influencing the polarization state of output light. All these influences cause the output voltage signal to be modulated deeply. Owing to the positive correlation between output voltage and light intensity, these stresses induced by dither bias surely affect the output intensity.[20]

The practical dithered angular movement amplitude is 2.9×10^{-4} rad, and frequency is 400 Hz. Assuming that in the original light the P-light and S-light each have an equivalent amount, the refraction index of the prisms is 1.45738. Figure 5 shows the simulation results of light intensity in the gyro after one circle propagation during the two dither periods, obtained from Eqs. (3) and (4) on the assumption that the deviation of the prism is zero.

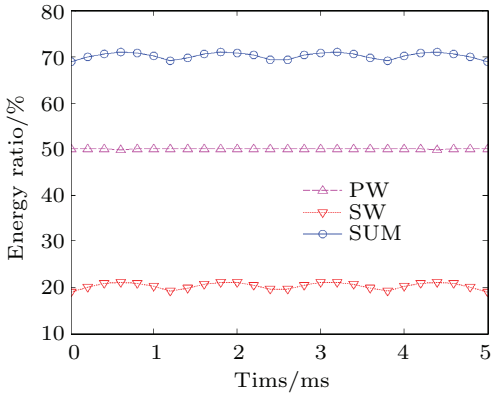


Fig. 5. (color online) Values of W_{out} when applied vibration with a frequency of 400 MHz and an amplitude of 2.9×10^{-4} rad in two dithered bias periods.

Figure 5 shows that during the dither periods, the output light intensity has a periodical change. The light intensity fluctuation extent is closely related to the gyro angular displacement. Due to the birefringence influence, S-polarized light can be maintained in the gyro under the above simulation condition. During the two dither periods, the ratio between standard deviation and mean of S light is 3.47%, while that of P light is 0.044% and that of the coupled light is 0.97%. For the results shown above, the birefringence occurring during the dither bias and the fluctuation extent of intensity of S light is more obvious than that of P

light. All these factors lead to dithered relative modulation depth phenomenon of this laser gyro. Moreover, unevenly prestressing distribution in prisms and the increasing dither amplitude can intensify the modulation depth extent of the output signal and influence the measurement accuracy of the laser gyro.

Currently, the prism assembly technique is usually manual. The assembly precision of the prism position has a direct influence on the trajectory of laser light in the gyro. In order to keep the light propagating in the gyro stay in a fundamental Gaussian mode, a diaphragm must be placed in the light transfer channel to limit the high order mode oscillation. As a result, the deviation of the light trajectory will significantly influence the intensity of coupled light on the combination prism.[21] Figure 6 shows the simulation results of intensity distribution of coupled light beams, in which the birefringence effect and different prism deviation extents are taken into account during a dither period.

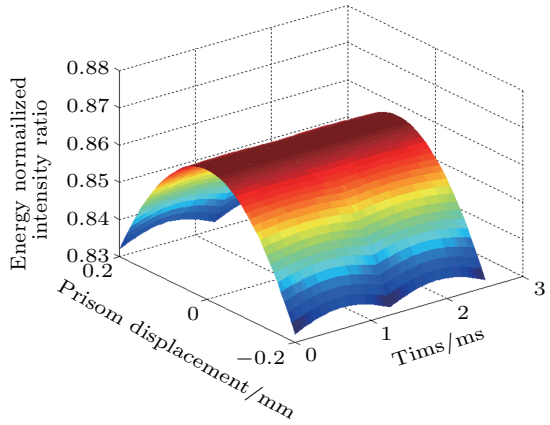


Fig. 6. (color online) Influence of prism deviation on coupled light intensity.

From Fig. 6 it is obviously seen that when the prism has an assembly error, the intensity of coupled light has a larger modulation depth. It has been calculated that if the deviation is more than 53% of the waist radial of laser light, the intensity of the output light can be attenuated to 84% of the original one, which affects the measurement accuracy of gyro greatly.

3.2. Analysis of polarization test results for gyros with different MD

In order to analyse the influence of dither bias on gyro output light polarization characteristics, PAT9000B was used to survey 10 sets of gyros. According to the polarization parameters mentioned above, 500-sampling surveys have been taken for each gyro. Table 1 shows the results of polarized parameters for gyros with different MDs in static and dither cases.

It can be derived from the data in Table 1 that the measurements in the static case are usually greater than those in the dither case. As for the polarized power, since there is no birefringence effect on output light, the static survey results are much greater than the results in the dither case.

Figure 7 shows the normalized distribution results of these polarization parameters for 10 sets of gyros at different MDs. While Fig. 8 shows the normalized distribution of standard deviations of these parameters.

According to the results in Fig. 7, it can be found that the correlation between the gyro MD value and the most polarized parameter is not significant except for the polarized power which has a proportional relationship with MD.

Standard deviation results depicted in Fig. 8 show that although in the static situation all parameters except polarized power do not have an obvious correlation with MD of gyros, they are proportional to the MD of gyros in the dither case generally. Compared with all measurement results, polarized power is the most obvious parameter in these standard deviation results that presents a positive correlation to the MD of gyros. Figure 9 shows the polarized power results for a gyro with MD being 1.2 V and 500 samplings in measurement.

Table 1. Survey results for gyros with different MDs in static and dither cases.

	Azimuth/(°)	Ellipticity/(°)	Delta/(°)	S_1	S_2	S_3	DOP/%	PSR	Power/dBm
Dithered data									
Maximum	18.1758	0.9743	5.9952	0.9775	0.5938	0.0337	100	0.9890	–18.7546
Minimum	6.0131	–0.3647	–2.5948	0.8039	0.2104	–0.0127	99.5945	0.9025	–30.9604
Static data									
Maximum	18.5133	–0.1612	–1.6284	0.7981	0.2016	–0.0096	100	0.8991	–16.6473
Minimum	5.6874	0.4231	1.4048	0.9794	0.6023	0.0144	99.9652	0.9902	–28.6190

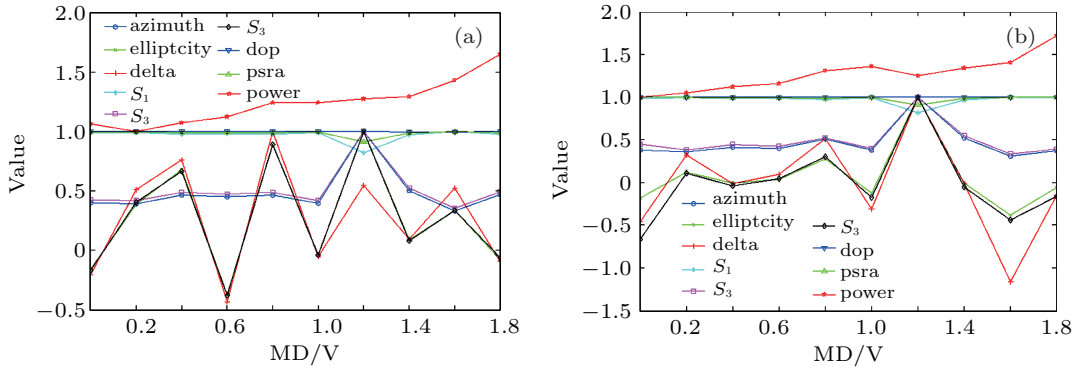


Fig. 7. (color online) Normalized distribution results of polarization parameters for 10 sets of gyros at different MDs for (a) dither case and (b) static case.

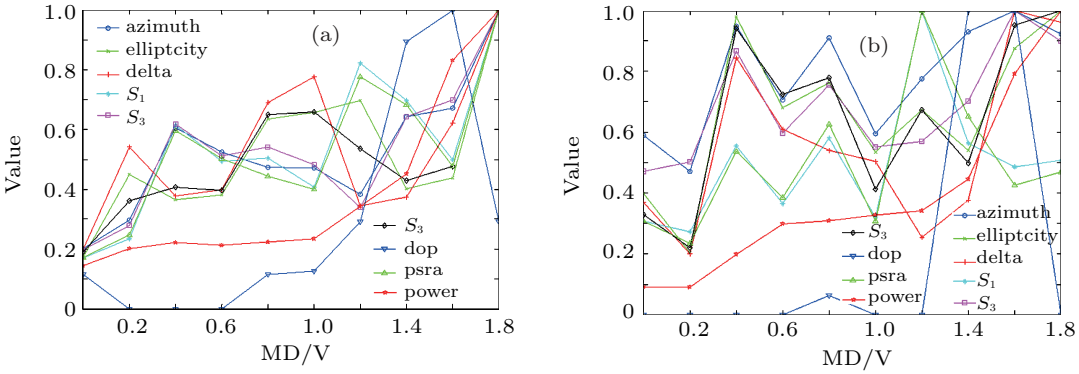


Fig. 8. (color online) Normalized distribution results of standard deviation of polarization parameters for 10 sets of gyros at different MDs for (a) dither case and (b) static case.

The solid line in Fig. 9 represents a fitted result by using linear weighting ordinary least squares to practical measurements. It can be found that polarized power of output light in the dither case is smaller than that in the static case, while the standard deviation is much larger instead. These results represent that the intensity of the output light is influenced by dither bias and its stability becomes worse as well. Figure 10 shows the mean and standard deviation of polarized power for 10 sets of gyros with different MDs.

According to the measurements results depicted above, it is found that with the increase of MD value, the polarized power of output light decreasing nonlinearly, and that the dither situation is always below that in a static situation, while the distribution of standard deviation is on the contrary instead. When the value of output polarized power is below 25.5% of that in a static ideal situation and the standard error is over 0.0337 dBm, the amplitude modulation extent of gyro output signal would be up to 16% according the experiments results above.

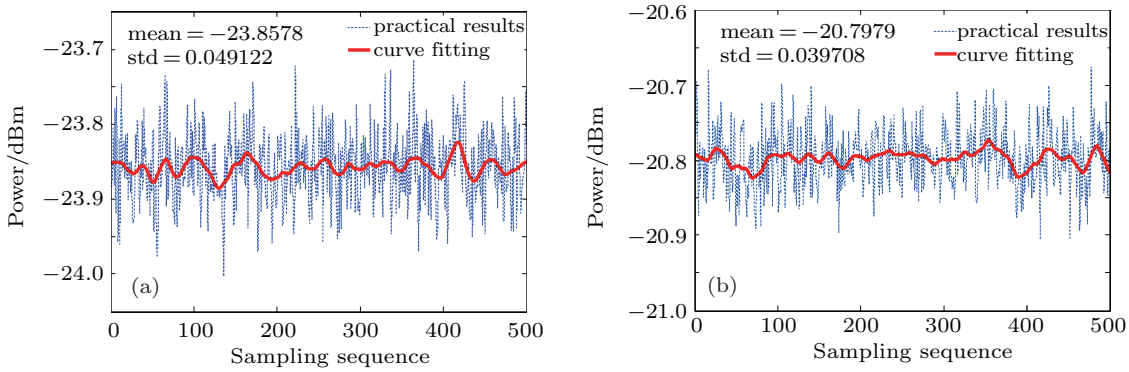


Fig. 9. (color online) Polarized power results for a gyro with MD being 1.2 V and 500 sampling results for (a) dither case and (b) static case.

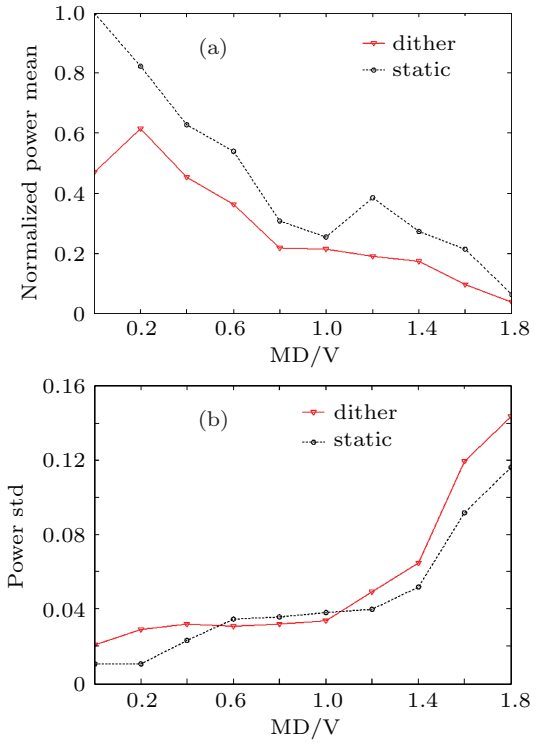


Fig. 10. (color online) Polarized power results for 10 sets of gyro: (a) 500-sampling mean result; (b) 500-sampling standard deviation result.

4. Conclusion

Theoretical analysis and experimental research on the polarization properties of output light in gyro are carried out, with with a focus on the phenomenon that the amplitude of output voltage signal is modulated by dither bias in laser gyros consisting of totally reflecting prisms. Ignoring the gyro structure type and assembly manner of the photodetector and taking the birefringence effect of the prism into account, the analytical formula of output light intensity in the gyro and the relationship between polarized parameters and MD are obtained and discussed. For first time, the polarized power value of output light is adopted as a basis to estimate the output signal amplitude fading extent of laser gyros. Analyses and measurements demonstrate that mechanical dither could induce the birefringence effect in a prism, which makes the laser propagate in the gyro off axis and affects the polarized light power greatly. As for the gyro in this paper, when the value of output light polarized power is below 25.5% of that in an ideal static situation, which equals −23.334 dBm, the standard error is over 0.0337 dBm, and when the displacement extent of the prism is higher than 53% of the radius of the beam waist in the gyro cavity, the amplitude modulation extent of gyro output signal reaches up to 16%, which badly influences the measurement accuracy of the laser gyro.

According to the above results, the production efficiency can be improved and the development cycle can be shortened by testing the polarized power of output light. The moment prisms are assembled in the gyro. In the gyro design, adopting suitable prisms, using a symmetrical structure, optimizing the assembly prism technique, and reducing the deviation of light can mitigate the modulation depth effect on the output signal of gyro evidently.

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