

Analysis and Design of 2×4 90° Crystal Space Optical Hybrid for Coherent Optical Communication

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Abstract: Based on the principles of crystal birefringence, wave plate phase delay and polarization transformation, a 2×4 90 degree crystal optical hybrid is presented. The beam splitting and coupling between signal and local oscillator lights of the hybrid is realized by two birefringent crystals and two half wave plates, and the required phase shift is produced by a quarter wave plate. Combined with the actual situation, the schemes of phase compensation and power ratio adjustment are given to optimize the performance of the device. And the feasibility of phase compensation and splitter ratio adjustment scheme is simulated and analysed through the establishment of mathematical model according to Jones matrix. The results show that the phase difference and splitter ratio can be set simply and accurately by the scheme of phase compensation and splitter ratio adjustment. Meanwhile, compared with the previous crystal spatial optical hybrid, this hybrid can improve the coupling effect of signal beam and local oscillator beam, and reduce the influence of crystal processing error between in-phase and quadrature branch. It has the advantages of simple and compact structure and good performance, and can be used in free-space optical coherent optical communication system.

Keywords: Coherent Optical Communication, Optical Hybrid, Birefringence Effect, Phase Compensation

1. Introduction

In the field of satellite-to-ground communication, free space coherent optical communication is the main way to improve the sensitivity of receiver and realize long distance, large capacity and high bit rate laser communication [1-5]. As the key device of coherent optical communication terminal, the purpose of optical hybrid is to split and combine the beam of the signal and local oscillator beams to produce four mixed beams with relative phase shift of 0°, 90°, 180° and 270°, which is convenience to process the subsequent coherent detection information, and its performance has a great influence on the subsequent coherent reception [6-8].

At present, the design scheme of the more mature space optical hybrid is mainly to the splitting and coupling is realized by the beam splitter, and the phase difference between the output beams is realized through the wave plate [9-11]. However, these schemes have the shortcomings of too many related components, large insertion loss and difficult to

integrate. Wan proposed an electronically controlled phase-shifted crystal space optical hybrid. The hybrid uses two-two stacked crystals to realize separation and combination of the signal and local oscillator beams, and solves the shortcomings that are more related elements and not easy to integrate [12]. However, the phase compensation of the structure is achieved by electro-optic modulation, which is necessary to plate electrodes on the crystal so that the stacked crystals cannot be completely parallel, thus affecting the phase shift output and coupling effect of the hybrid. A crystal hybrid based on the combination of crystal birefringence and wave plate is proposed in reference [13-15]. Although the required phase of the hybrid is introduced by the wave plate, which does not need to plat an electrode on the crystal, the crystal structure requirements are exactly the same, and the machining error of the crystals will also affect the phase shift output and coupling effect of the hybrid.

In this paper, a crystal optical hybrid which suitable for free space coherent optical communication is designed, and the schemes of phase compensation and split ratio adjustment are

given. The coherent mixing principle of the hybrid and the optimized structure is analyzed to verify the performance of the hybrid and the feasibility of the phase compensation and power ratio adjustment scheme.

2. Crystal Optical Hybrid

2.1. Structural Design

The schematic diagram of the 2×4 90 degree crystal optical

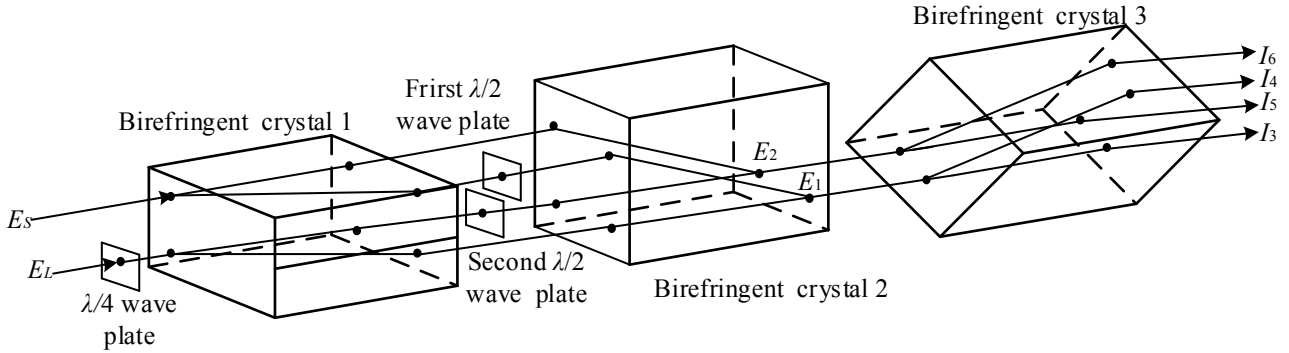


Figure 1. Schematic diagram of crystal optical hybrid (E_S : the signal laser beam, E_L : the local oscillator beam, I_3, I_4, I_5, I_6 : the four mixed output beams).

When the signal beam E_S with a polarization orientation of 45 degree is incident into the first birefringent crystal, it is divided into the signal ordinary beam E_{S_o} and extraordinary beam E_{S_e} with their have equal amplitude due to the birefringence effect of the crystal. The local oscillator beam E_L is also divided into the local oscillator ordinary beam E_{L_o} and extraordinary beam E_{L_e} with their have equal amplitude when the beam incident into the first birefringent crystal after passing through the quarter wave plate.

Subsequently, after the local oscillator e-light and signal o-light respectively pass through the first and second half wave plates to change their polarization direction, they enter the birefringent crystal 2 together with the local oscillator e-light and the signal o-light. Because the main cross section of birefringent crystal 2 is perpendicular to the birefringent crystal 1, the four beams are coupled at the lower part of the exit plane of the birefringent crystal 2 to form two mixed beams E_1 and E_2 . The angle between the main cross section of the crystal 1 and crystal 2 is 45 degree. The two mixed beams E_1 and E_2 emitted from the crystal 2 pass through the crystal 3 respectively. The spatial separation, in the crystal 3, is generated to form four mixed lights I_3, I_4, I_5 and I_6 , and the function of 90 degree optical hybrid is completed.

2.2. Principle Analysis

The input signal beam E_S and local oscillator beam E_L are linearly polarized beams, and the polarization direction is 45 degree to the main cross section of the first birefringent crystal and the fast axis of the quarter wave plate respectively. The complex amplitude of the beams field can be expressed as follows:

hybrid is shown in figure 1, which is mainly composed of three birefringent crystals, two half and a quarter wave plates. Among them, the main cross sections of birefringent crystal 1 and crystal 2 are perpendicular to each other, and the angle of main cross section between birefringent crystal 3 and crystal 2 is 45 degree. The fast axis of the quarter wave plate is parallel to the horizontal direction. The angle is 45 degree between the fast axis of the first and second half wave plates and horizontal direction.

$$E_S = \frac{\sqrt{2}}{2} A_S \begin{bmatrix} 1 \\ 1 \end{bmatrix} \exp\{i[\omega_S t + \phi(t) + \phi_{S_0}]\} \quad (1)$$

$$E_L = \frac{\sqrt{2}}{2} A_L \begin{bmatrix} 1 \\ 1 \end{bmatrix} \exp[i(\omega_L t + \phi_{L_0})] \quad (2)$$

In formulas (1) and (2), A_S and A_L is the amplitude of the signal and local oscillator beams respectively, ω_S and ω_L represent the angular frequency of the input two beams respectively, ϕ_{S_0} and ϕ_{L_0} are the initial phase of the input two beams, and $\phi(t)$ is the phase modulation function of the signal beam.

The quarter wave plate with the fast axis parallel to the horizontal direction can be described by the matrix:

$$\Lambda_1 = \frac{\sqrt{2}}{2} \begin{pmatrix} 1-i & 0 \\ 0 & 1+i \end{pmatrix} \quad (3)$$

The expression of the four parallel beams after passing through the birefringent crystal 1 are expressed as follows:

$$E_{S_o} = \frac{\sqrt{2}}{2} A_S \begin{bmatrix} 0 \\ 1 \end{bmatrix} \exp\{i[\omega_S t + \phi(t) + \phi_{S_0} + \phi_{i_o}]\} \quad (4)$$

$$E_{S_e} = \frac{\sqrt{2}}{2} A_S \begin{bmatrix} 1 \\ 0 \end{bmatrix} \exp\{i[\omega_S t + \phi(t) + \phi_{S_0} + \phi_{i_e}]\} \quad (5)$$

$$E_{L_o} = \frac{\sqrt{2}}{2} A_L \begin{bmatrix} 0 \\ 1 \end{bmatrix} \exp\left[i(\omega_L t + \phi_{L_0} + \phi_{i_o} + \frac{\pi}{4})\right] \quad (6)$$

$$E_{Le} = \frac{\sqrt{2}}{2} A_L \begin{bmatrix} 1 \\ 0 \end{bmatrix} \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1e} - \frac{\pi}{4}) \right] \quad (7)$$

Where φ_{1o} and φ_{1e} represent the phase retardation of the o-light and e-light in crystal 1 respectively.

The half wave plate with the fast axis and the horizontal direction of 45 degree can be expressed as:

$$\Lambda_2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad (8)$$

After the polarization direction of the signal e-light and local oscillator o-light pass through the first and second half wave plates, the beams is mixed with the local oscillator e-light and signal o-light in the crystal 2 to form two beams of light E_1 and E_2 respectively. Their expression are as follows:

$$E_1 = \begin{bmatrix} \frac{\sqrt{2}}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1e} + \varphi_{2e}] \} \\ -\frac{\sqrt{2}}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1e} + \varphi_{2o} - \frac{\pi}{4}) \right] \end{bmatrix} \quad (9)$$

$$E_2 = \begin{bmatrix} \frac{\sqrt{2}}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1o} + \varphi_{2e}] \} \\ -\frac{\sqrt{2}}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1o} + \varphi_{2o} + \frac{\pi}{4}) \right] \end{bmatrix} \quad (10)$$

Where φ_{2o} and φ_{2e} represent the phase retardation of the o-ray and e-ray in crystal 2 respectively.

The two mixed beams E_1 and E_2 are separated into four mixed beams of signal and local oscillator after passing through the crystal 3, which are expressed as follows:

$$E_3 = -\frac{1}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1e} + \varphi_{2e} + \varphi_{3o}] \} - \frac{1}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1e} + \varphi_{2o} + \varphi_{3o} - \frac{\pi}{4}) \right] \quad (11)$$

$$E_4 = \frac{1}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1e} + \varphi_{2e} + \varphi_{3e}] \} - \frac{1}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1e} + \varphi_{2o} + \varphi_{3e} - \frac{\pi}{4}) \right] \quad (12)$$

$$E_5 = -\frac{1}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1o} + \varphi_{2e} + \varphi_{3o}] \} - \frac{1}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1o} + \varphi_{2o} + \varphi_{3o} + \frac{\pi}{4}) \right] \quad (13)$$

$$E_6 = \frac{1}{2} A_s \exp \{ i[\omega_s t + \phi(t) + \phi_{s0} + \varphi_{1o} + \varphi_{2e} + \varphi_{3e}] \} - \frac{1}{2} A_L \exp \left[i(\omega_L t + \phi_{L0} + \varphi_{1o} + \varphi_{2o} + \varphi_{3e} + \frac{\pi}{4}) \right] \quad (14)$$

Where φ_{3o} and φ_{3e} represent the phase retardation of the o-ray and e-ray in birefringence crystal 3.

Taking the output beam I_3 as the reference beam, the intensity expression of the four output beams under ideal conditions is obtained as follows:

$$I_3 = \frac{1}{4} |A_s|^2 + \frac{1}{4} |A_L|^2 + \frac{1}{2} |A_s| |A_L| \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) + \frac{\pi}{4}) \quad (15)$$

$$I_4 = \frac{1}{4} |A_s|^2 + \frac{1}{4} |A_L|^2 + \frac{1}{2} |A_s| |A_L| \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) + \frac{\pi}{4} + \pi) \quad (16)$$

$$I_5 = \frac{1}{4} |A_s|^2 + \frac{1}{4} |A_L|^2 + \frac{1}{2} |A_s| |A_L| \times \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{4}) \quad (17)$$

$$I_6 = \frac{1}{4} |A_s|^2 + \frac{1}{4} |A_L|^2 + \frac{1}{2} |A_s| |A_L| \times \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{4} + \pi) \quad (18)$$

It can be seen from formulas (15) to (18) that the four mixed beams I_3 , I_4 , I_5 and I_6 of the signal and local oscillator beams have relative phase shifts of 0° , 180° , 90° and 270° respectively. That is to say, the four-channel output beams with 90 degree phase shift. The function of 90 degree optical hybrid is realized.

At the same time, it also can be seen from formulas (15) to (18) that the crystal hybrid is different from the literature [13-15]. The hybrid does not need the same crystal structure to ensure that the phase delay of beam in the crystal is equal. Compared with the previous crystal optical hybrid, the influence of crystal processing error the hybrid on the phase shift output function of the is reduced, and the beam separation and combination of the signal and local oscillator beams are complete by only two

crystals. It is helpful to reduce the difficulty of system installation and improve the coupling effect.

3. Structural Optimization

3.1. Phase Compensation Scheme

In practical application, there is always some deviation in the phase shift of the hybrid due to the influence of various factors, so the phase is compensated necessary. The phase shift of the hybrid is provided by the quarter wave plate, and if the wave plate is rotates a small angle, in which case the Jones matrix of the wave plate can be described as [9]:

$$\Lambda_3 = \begin{bmatrix} 1 & \delta \\ -\delta & 1 \end{bmatrix} \Lambda_1 \begin{bmatrix} 1 & -\delta \\ \delta & 1 \end{bmatrix} = \begin{bmatrix} e^{-i\frac{\pi}{4}} & -\sqrt{2}i\sigma \\ -\sqrt{2}i\sigma & e^{-i\frac{\pi}{4}} \end{bmatrix} \quad (19)$$

Through the same analysis, the final output intensity of the four beams are:

$$I_3 = \frac{1}{4}|A_S|^2 + \frac{1}{4}|A_L|^2 + \frac{1}{2}|A_S||A_L| \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) + \frac{\pi}{4}\right) + \frac{\sqrt{2}}{2}|A_S||A_L|\sigma \times \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{2}\right) \quad (20)$$

$$I_4 = \frac{1}{4}|A_S|^2 + \frac{1}{4}|A_L|^2 + \frac{1}{2}|A_S||A_L| \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) + \frac{\pi}{4} + \pi\right) - \frac{\sqrt{2}}{2}|A_S||A_L|\sigma \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{2}\right) \quad (21)$$

$$I_5 = \frac{1}{4}|A_S|^2 + \frac{1}{4}|A_L|^2 + \frac{1}{2}|A_S||A_L| \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{4}\right) + \frac{\sqrt{2}}{2}|A_S||A_L|\sigma \times \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{2}\right) \quad (22)$$

$$I_6 = \frac{1}{4}|A_S|^2 + \frac{1}{4}|A_L|^2 + \frac{1}{2}|A_S||A_L| \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{4} + \pi\right) - \frac{\sqrt{2}}{2}|A_S||A_L|\sigma \times \cos\left((\omega_S - \omega_L)t + \phi(t) + (\phi_{S0} + \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \frac{\pi}{2}\right) \quad (23)$$

It can be seen that the phase of the hybrid can be compensated by rotating quarter wave plate and the phase accuracy is improved. However, the power ratio between the in-phase and quadrature (I/Q) branch is changed caused by the rotation of the quarter wave plate. A method is needed to adjust the power ratio.

3.2. Spectral Ratio Adjustment Scheme

Similar to the polarization splitter spatial optical hybrid in reference [16], the power ratio of the crystal optical hybrid is adjusted by adding a half wave plate in the signal beam path. The structure diagram is shown in figure 2, and the structure of the optimized 2×4 90 degree crystal optical hybrid principle is as follows:

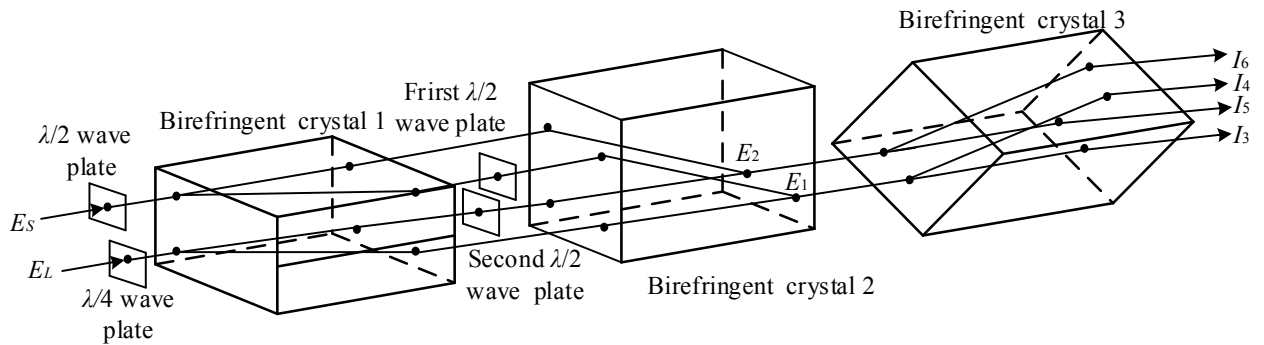


Figure 2. Structure of the optimized 2×4 90 degree crystal optical hybrid.

The angle between the fast axis of the quarter wave plate and the horizontal direction is β_1 , and the angle between the fast axis of the half wave plate of signal optical path and the horizontal direction of is β_2 . Respectively, Their Jones matrix are described by

$$\Lambda_4 = \frac{\sqrt{2}}{2} \begin{pmatrix} 1 - i \cos 2\beta_1 & -i \sin 2\beta_1 \\ -i \sin 2\beta_1 & 1 + i \cos 2\beta_1 \end{pmatrix} \quad (24)$$

$$\Lambda_5 = \begin{pmatrix} \cos 2\beta_2 & \sin 2\beta_2 \\ \sin 2\beta_2 & -\cos 2\beta_2 \end{pmatrix} \quad (25)$$

Similarly, the intensity of the final output of four mixed beams are as follows:

$$I_3 = \frac{1}{4} |A_s (\sin 2\beta_2 + \cos 2\beta_2)|^2 + \frac{1}{8} |A_L \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2}|^2 + \frac{\sqrt{2}}{4} |A_s| |A_L| \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2} \times (\sin 2\beta_2 + \cos 2\beta_2) \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_1) \quad (26)$$

$$I_4 = \frac{1}{4} |A_s (\sin 2\beta_2 + \cos 2\beta_2)|^2 + \frac{1}{8} |A_L \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2}|^2 + \frac{\sqrt{2}}{4} |A_s| |A_L| \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2} \times (\sin 2\beta_2 + \cos 2\beta_2) \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_1 + \pi) \quad (27)$$

$$I_5 = \frac{1}{4} |A_s (\sin 2\beta_2 - \cos 2\beta_2)|^2 + \frac{1}{8} |A_L \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2}|^2 + \frac{\sqrt{2}}{4} |A_s| |A_L| \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2} \times (\sin 2\beta_2 - \cos 2\beta_2) \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_2) \quad (28)$$

$$I_6 = \frac{1}{4} |A_s (\sin 2\beta_2 - \cos 2\beta_2)|^2 + \frac{1}{8} |A_L \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2}|^2 + \frac{\sqrt{2}}{4} |A_s| |A_L| \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2} \times (\sin 2\beta_2 - \cos 2\beta_2) \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_2 + \pi) \quad (29)$$

Where $\varphi_1 = \arctan(\cos 2\beta_1 - \sin 2\beta_1)$, $\varphi_2 = -\arctan(\cos 2\beta_1 + \sin 2\beta_1)$.

If I_3 is also used as the reference light, there are:

$$I_3 - I_4 = \frac{\sqrt{2}}{2} |A_s| |A_L| (\sin 2\beta_2 + \cos 2\beta_2) \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2} \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_1) \quad (30)$$

$$I_5 - I_6 = \frac{\sqrt{2}}{2} |A_s| |A_L| (\sin 2\beta_2 - \cos 2\beta_2) \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2} \cos((\omega_s - \omega_L)t + \phi(t) + (\phi_{s0} - \phi_{L0}) + (\varphi_{2e} - \varphi_{2o}) - \varphi_2) \quad (31)$$

The power ratio between the I/Q branches is:

$$\frac{\langle I_3 - I_4 \rangle_{\max}}{\langle I_5 - I_6 \rangle_{\max}} = \frac{(\sin 2\beta_2 + \cos 2\beta_2) \sqrt{1 + (\cos 2\beta_1 + \sin 2\beta_1)^2}}{(\sin 2\beta_2 - \cos 2\beta_2) \sqrt{1 + (\cos 2\beta_1 - \sin 2\beta_1)^2}} \quad (32)$$

From the formulas (30) and (31), it can be seen that the angle between the fast axis of the quarter wave plate and horizontal direction will affect the phase and power ratio of the hybrid, which proves once again the feasibility of the phase compensation scheme in the previous section. From the formula (32), it can be known that the angle between the fast axis of the half wave plate and horizontal direction will only affect the spectral ratio of the hybrid. Therefore, the phase can be compensated by rotating the optical axis of the quarter wave plate, and then the half wave plate can be rotated to compensate for the change of the power ratio caused by the phase compensation, so as to improve the performance of the hybrid.

4. Performance Analysis

4.1. Scheme Design

In order to separate the beam as far as possible in the crystal, maximum deviation of the beam is adopted. Let the refractive index of o-ray and e-ray in the crystals is n_o and n_e respectively.

For negative uniaxial crystal, the optical axis angle θ_m of the crystal is [13]

$$\theta_m = \arctan \frac{n_o}{n_e} \quad (33)$$

The maximum deviation angle α_m of beam in the crystal is [13]

$$\alpha_m = \arctan \left(\frac{n_o^2 - n_e^2}{2n_o n_e} \right) \quad (34)$$

The maximum separation distance ΔL of beam in the crystal is [13]

$$\Delta L = D \tan \alpha_m \quad (35)$$

In view of the fact that the calcite crystal has large birefringence and the beam deviation angle is relatively large, the complete separation of o-ray and e-ray can be obtained in a short distance, so the calcite is selected as the birefringent crystal material. Assuming that the wavelength is 632.8 nm, the spot diameter of the signal and local oscillator beams is 3mm. Under these conditions, $n_o=1.6557$, $n_e=1.4862$, the maximum separation angle of the light in the crystal is 6.18° and the optical axis orientation is 48° by calculates. In order to

facilitate processing. the sizes of three crystals are all 40mm×15mm×15mm. The separation distance of the beam is 4.324mm.

4.2. Phase Compensation and Split Ratio Adjustment Analysis

As can be seen from the above section, the phase and the split ratio of the optical hybrid can be separately compensated and adjusted by rotating the optical axes of the quarter wave plate in the local oscillator optical path and the half wave plate in the signal optical path. According to the device parameters designed in the previous section, the effects of the phase difference and power ratio of rotating the quarter and half wave plates are simulated and analyzed. Figure 3 is the

transformation of phase and power ratio between the I/Q branches when β_2 is 45° and the optical axis of quarter wave plate is rotated. As shown in Figure 3(a), when the quarter wave plate rotates between -180° and 180° , there are five positions to ensure the signal is orthogonal between the I/Q branches. Therefore, it is possible to compensate for the phase difference due to factors such as crystal processing and system mounting error. At the same time, the power ratio between the I/Q branches also changes due to the rotation of the quarter wave plate. As shown in Figure 3(b), the splitting ratio changes when the rotation of the quarter wave plate is rotated by one rotation, and the range of variation is between 0.58 and 1.73. Therefore, it is necessary to adjust the power ratio by rotating the half wave plate in the signal optical path.

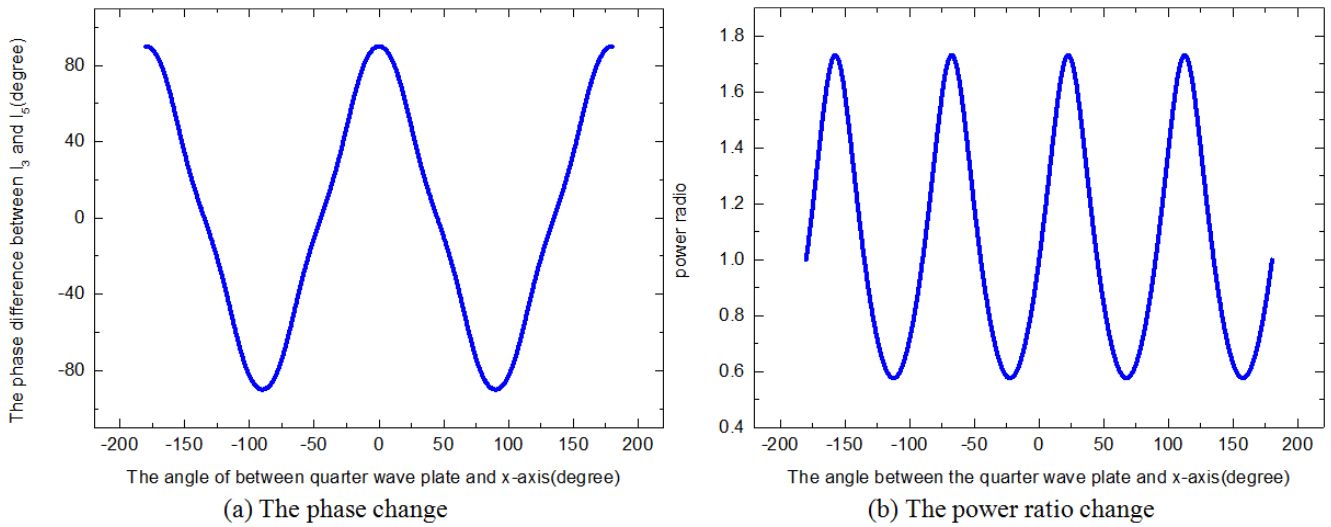


Figure 3. The effect of 90 degree hybrid when $\beta_2=45^\circ$ and rotating quarter plate optical axis.

Figure 4 shows the changes of the phase and split ratio between the I/Q channels when β_1 is 0 and the optical axis of the half wave plate in the signal optical path is rotated. It can be seen from Figure 4(a) that the phase between the I/Q paths does not change when β_2 is between 35° and 55° , that is to say, the phase of hybrid without changes when the optical axis

of the half wave plate is rotated. Figure 4(b) shows the change of the splitting ratio when the half wave plate is rotated. It can be seen from the figure that when β_2 is within the range, the splitting ratio decrease with the increase of β_2 , and the change of power ratio caused by phase difference compensation or other factors can be adjusted.

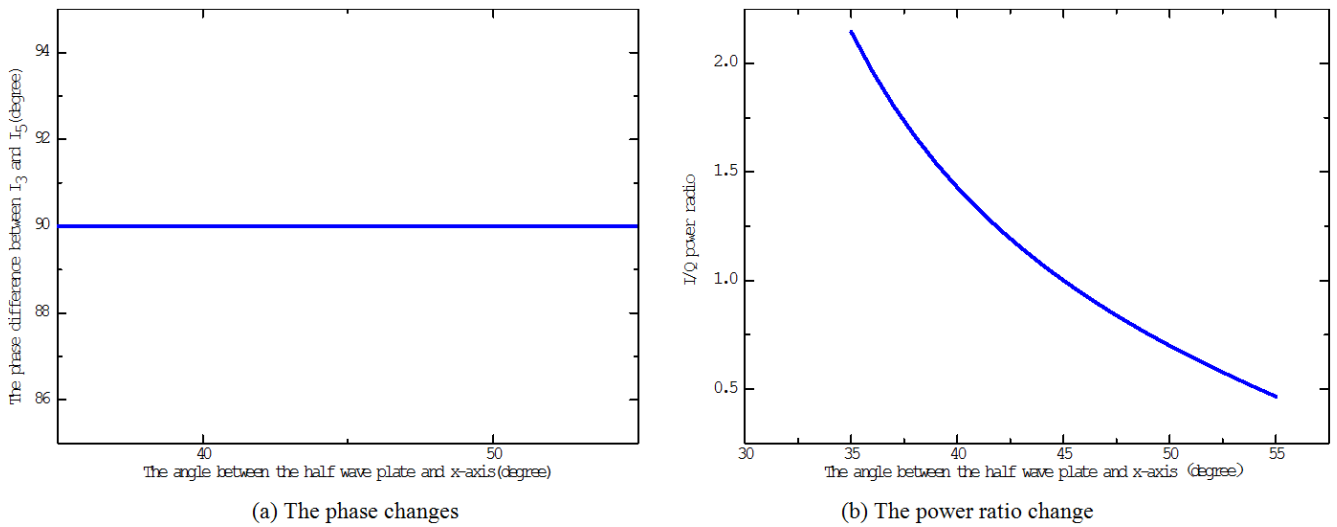


Figure 4. The effect of 90 degree hybrid when $\beta_1=0^\circ$ and rotating half wave plate optical axis.

5. Conclusion

Based on the principles of crystal birefringence, wave plate phase delay and polarization transformation, a 2×4 90 degree crystal optical hybrid is presented, and the phase compensation and the adjustment scheme of power ratio between the in-phase and quadrature branch due to phase compensation are given. Compared with the previous hybrid structure, the structure does not require the same crystal structure to ensure the same phase delay, so that the influence of the crystal processing error on the phase shift of the hybrid is reduced and the phase accuracy is improved. And there is no need for pairwise crystal stacking so the crystal is reduced, the difficulty of system installation is reduced, and the coupling effect is improved. At the same time, the scheme of phase compensation and power ratio adjustment are simple and accurate to set the required phase difference and power ratio. The hybrid has the advantages of simple and compact structure and good performance, and is suitable for free space coherent optical communication.

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References

- [1] Painchaud Y., Poulin M., Morin M., Têtu M. (2009) Performance of balanced detection in a coherent receiver. *Optics Express*, 17, 3659-3672.
- [2] Torre A. D., Marini A. E., Musetti P. (1990) Coherent detection in optical space communication based on diode-pumped Nd lasers technology. *International Society for Optics and Photonics*, Los Angeles, Ca. USA, 1218, 456-466.
- [3] Lange, R., Smutny B. (2005) Highly-coherent optical terminal design status and outlook. *Digest of the LEOS Summer Topical Meetings*, San Diego, CA, USA, 55-57.
- [4] Cartledge J. C., Downie J. D., Hurley J. E., Zhu X. M., Roudas L. (2012) Bit Error Ratio Performance of 112 Gb/s PM-QPSK Transmission Systems. *Journal of Lightwave Technology*, 30, 1475-1479.
- [5] Seel S., Troendle D., Heine F., Zech H., Motzigemba M., Sterr U. (2014) Alphasat laser terminal commissioning status aiming to demonstrate Geo-Relay for Sentinel SAR and optical sensor data. *International Geoscience and Remote Sensing Symposium*, Quebec, Canada, 100-101.
- [6] Kazovsky L. G. (1985) Decision-driven phase-locked loop for optical homodyne receivers: Performance analysis and laser linewidth requirements. *Journal of Lightwave Technology*, 3, 1238-1247.
- [7] Banerjee A., Biswas B. N. (2013) BPSK homodyne receivers based on modified balanced optical phase-locked loop. *Optik*, 124, 994-997.
- [8] Fabrega J. M., Vilabru L., Prat J. (2008) Experimental demonstration of Heterodyne Phase-Locked Loop for optical homodyne PSK receivers in PONs. *Anniversary International Conference on Transparent Optical Networks*, Athens, Greece, 222-225.
- [9] Garreis R. B. (1991) 90 degree optical hybrid for coherent receivers. *Optical Space Communication II*. *International Society for Optics and Photonics*, St. Petersburg, Russia, 1522, 210-219.
- [10] Zhou Y., Wan L. Y., Zhi Y. N., Luan Z., Sun J. F., Liu L. R. (2009) Polarization-Splitting 2×4 90° Free-Space Optical Hybrid with Phase Compensation. *Acta optica sinica*, 29, 3291-3294.
- [11] Li J. S., Billah M. R., Schindler P. C., Lauermaun M., Schuele S., Hengsbach S., Hollenbach U., Mohr J., Koos C., Freude W., Leuthold J. (2013) Four-in-one interferometer for coherent and self-coherent detection. *Optics Express*, 21, 13293-13304.
- [12] Wan L. Y., Da S. S., Liu L. R. (2008) A new 90° hybrid for coherent receivers in free-space laser communications. *Proceedings of SPIE - The International Society for Optical Engineering*, San Diego, California, USA, 7158, 71580D.
- [13] Wan L. Y., Zhou Y., Liu L. R., Sun J. F. (2013) Realization of a free-space 2×4 90° optical hybrid based on the birefringence and electro-optic effects of crystals. *Journal of Optics*, 15, 0354022.
- [14] Hou P. P., Zhou Y., Zhi Y. N., Sun J. F., Liu L. R. (2011) An Optical 2×4 90° Hybrid Based on a Birefringent Crystal for a Coherent Receiver in a Free Space Optical Communication System. *Chinese physical letter*, 28, 074204.
- [15] Zhi Y. N., Zhou Y., Liu L. R. (2010) Optical 90-deg hybrid of birefringent crystals for freely propagating laser beams. *Optical Engineering*, 49, 125004.
- [16] H. S. Cao, L. Jiang, P. Zhang, H. Nan, S. F. Tong, L. Z. Zhang, (2017) Power ratio adjustment and 90° phase difference compensation method of space optical hybrid. *Acta optica sinica*, 46, 139-145.