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Enbang Li

Tianjin University, enbang@uow.edu.au

Jianquan Yao

Tianjin University

Daoyin Yu

Tianjin University

Jiangtao Xi

University of Wollongong, jiangtao@uow.edu.au

Joe F. Chicharo

University of Wollongong, chicharo@uow.edu.au

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Abstract

A novel optical phase-shifting method based on a well-known acousto-optic interaction is proposed. By using a pair of acousto-optic modulators (AOMs) and properly aligning them, we construct an optical phase shifter that can directly control the phase of a collimated beam. The proposed phase shifter is insensitive to the polarization of the incident beam when polarization-insensitive AOMs are used, and no calibration is necessary. The proposed approach is confirmed with experimental results.

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Optical phase shifting with acousto-optic devices

Enbang Li

College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China, and
School of Electrical, Computer and Telecommunications Engineering, Faculty of Informatics, University of Wollongong,
Wollongong, NSW 2522, Australia

Jianquan Yao and Daoyin Yu

College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

Jiangtao Xi and Joe Chicharo

School of Electrical, Computer and Telecommunications Engineering, Faculty of Informatics, University of Wollongong,
Wollongong, NSW 2522, Australia

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Optical phase shifting is desired in various interference-based optical experiments and systems, including stellar interferometry,¹ lateral shearing interferometry,^{2,3} phase-measuring profilometry,⁴ and holographic interferometry.⁵ Optical phase shifts can be introduced in various ways. Mechanically translating an optical mirror or a grating can introduce phase shifts into a reflected or diffracted light beam. These mechanical translations can be achieved with a stepping motor or a piezoelectric transducer. As can be appreciated, accuracy, stability, and dynamic response are main issues in the application of mechanical methods owing to their inherent characteristics such as hysteresis and thermal drift.

An alternative method for introducing phase shifting, called geometric phase shifting, is based on the effect of an analyzer on two coherent beams with different states of polarization.^{6–9} One obvious advantage of a geometric phase shifter is that it is achromatic, which is essential for many applications. More recently, another achromatic optical shifter that uses a frequency-domain optical delay line and a tiltable mirror was reported.¹⁰

For all the phase-shifting methods mentioned above, mechanical motion is necessary to vary the phase shifts. It is desirable to develop optical phase-shifting methods that can generate variable phase shifts without moving parts and can be controlled electronically. Furthermore, in all the existing phase-shifting methods, phase shifts are indirectly introduced; hence calibration is necessary before use. In some cases the calibration process can be tedious and time consuming. More importantly, the measurement accuracy depends on the calibration accuracy.

In this Letter we propose and demonstrate a novel optical phase-shifting method. By utilizing a pair of

acousto-optic modulators (AOMs) we introduce optical phase shifts in a laser beam through control of the phase delay between two RF sinusoidal signals. The proposed phase shifter is insensitive to the polarization of the incident beam when polarization-insensitive AOMs are used. To our knowledge, this is the first optical phase-shifting method by which phase shifts can be directly introduced into a collimated beam. A schematic diagram of the phase-shifting setup is shown in Fig. 1. Two AOMs, AOM1 and AOM2, are arranged in tandem. The incident laser beam is diffracted by AOM1, and the first diffraction order is taken as the incident beam of AOM2. The RF driving signals to AOM1 and AOM2 are of the same frequency but with a phase delay between them.

Suppose that the electric field of the incident beam is

$$E(z_0, t) = E_0 \exp[i(k_0 z_0 - \omega_0 t)] \quad (1)$$

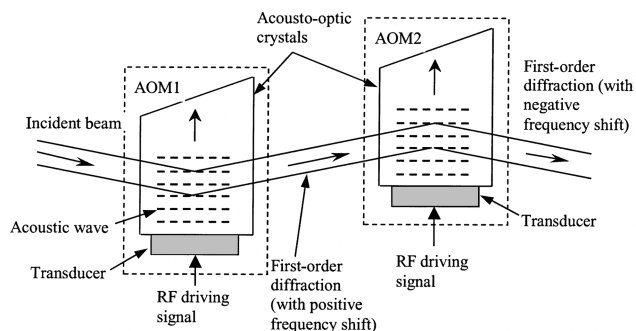


Fig. 1. Schematic diagram of the proposed optical phase shifter.

and the field of the acoustic wave in the first acousto-optic crystal is

$$A_1 = A_{10} \exp[i(KX - \Omega t + \Phi_1)]. \quad (2)$$

Inside the crystal, the density (and hence the refractive index) of the material is modulated by the presence of the acoustic wave. The refractive-index modulation acts as a moving grating in the crystal. When the angle of incidence satisfies the so-called Bragg condition, the incident beam is diffracted into either a +1 or a -1 diffraction order. As the grating is moving, the diffracted beams are also frequency shifted. Depending on the direction of the incident beam relative to the acoustic wave, the frequency shifts can be either positive or negative. If the incident beam is toward the moving direction of the acoustic wave, as shown in Fig. 1, a positive frequency shift will be generated to the +1-order diffraction. The shifted frequency is equal to the frequency of the driving signal applied to the transducer. Therefore, at the exit of the first modulator, AOM1, the electric field of the first-order diffracted beam becomes

$$E_1(z_1, t) = E_{10} \exp\{i[k_1 z_1 - (\omega_0 + \Omega)t + \varphi_1 + \Phi_1]\}, \quad (3)$$

where φ_1 is a phase delay associated with the optical path from the entrance to the exit of AOM1. The first-order diffracted beam generated by AOM1 enters the second modulator, AOM2, in which the field of the acoustic wave can be expressed as

$$A_2 = A_{20} \exp[i(KX - \Omega t + \Phi_2)]. \quad (4)$$

Note that, by contrast with the first modulator (AOM1), AOM2 is arranged such that the incident beam is along the moving direction of the acoustic wave. Therefore a negative frequency shift is added to the first-order diffracted beam generated by AOM2. As the two AOMs are driven by the signals with the same frequency, the frequency shift generated by AOM1 will be removed. The electric field of the first-order diffracted beam of AOM2 can be expressed as

$$E_2(z_2, t) = E_{20} \exp\{i[k_2 z_2 - \omega_0 t + \varphi_2 + \Phi_1 - \Phi_2]\}, \quad (5)$$

where φ_2 is a phase delay caused by the total optical path from the entrance of AOM1 to the exit of AOM2.

It can be seen that, after passing through the two AOMs, the laser beam picks up an extra phase delay, $\varphi_2 + \Phi_1 - \Phi_2$. As φ_2 is a constant once the AOMs are aligned, the phase of the output beam is completely determined by $\Phi_1 - \Phi_2$, which is the phase delay between the two RF driving signals applied to the AOMs. Therefore, by controlling the phase delay between the two RF driving signals, one can directly vary the phase of the output beam as required.

To demonstrate the phase-shifting technique we set up an interferometer as shown in Fig. 2. An unpolarized laser beam from a 5-mW He-Ne laser was split by a beam splitter into two beams. One of the two

beams was reflected by a mirror, and the other entered the phase shifter consisting of AOM1 and AOM2. The material of the acousto-optic crystals was PbMnO_4 . The first-order diffraction efficiency of the AOMs was $\sim 80\%$. To select the first-order diffracted beams we used two spatial filters. The output beam from the phase shifter and the beam reflected by the mirror were brought together by a focusing lens. At the area of intersection, interference fringes were produced. To view the fringes, we projected them onto a screen by using a microscope objective. A CCD detector was positioned in the projected fringe field to capture the fringe patterns. The RF signal generated by a crystal oscillator was simultaneously fed into a power amplifier for driving AOM1 and a programmable digital delay line that acts as an electronic phase shifter. The phase-shifted RF signal was amplified by the second power amplifier before being fed to AOM2. The frequency of the RF driving signals was 65 MHz, giving a period of 15.38 ns. The increment of the programmable digital delay line was 0.25 ns. This means that a phase resolution of $\sim 6^\circ$ could be achieved. The phase delays between the two AOM driving signals were monitored and measured with a digital oscilloscope.

The phase delays between the two AOM driving signals were set by an 8-bit code in the experiments. At different phase delays, the fringe patterns were recorded by the CCD detector. Movement of the fringe pattern was observed when the phase delay was varied. Figure 3 depicts two typical fringe images that correspond to a nominal phase shift of 180° . Our experiments have conclusively confirmed that the proposed phase-shifting method is feasible.

As can be seen from Eq. (5), the phase delay of the output beam of the phase shifter is also related to the total optical path from the entrance of AOM1 to the exit of AOM2. This means that optical path variations caused by the change of temperature, for instance, could introduce errors and instability. More-detailed experiments to examine the accuracy and stability of the introduced phase shifts are currently under way.

In conclusion, we have proposed and demonstrated experimentally a novel optical phase-shifting method based on the well-known acousto-optic interaction. Acousto-optic modulators have been widely used as frequency shifters in various applications. To the

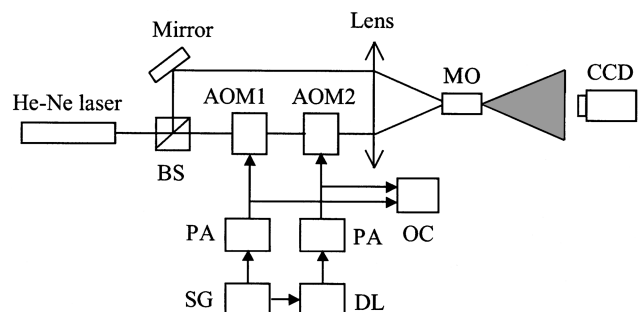


Fig. 2. Experimental setup to demonstrate the proposed phase-shifting method: BS, beam splitter; PAs, power amplifiers; SG, signal generator; DL, delay line; OC, oscilloscope; MO, microscope objective.

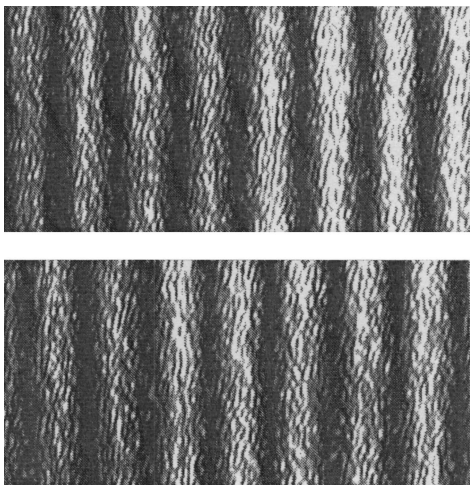


Fig. 3. Fringe patterns recorded with a phase delay of 180° .

best of our knowledge, this is the first demonstration that optical phase shifting can also be achieved by use of acousto-optic devices. The proposed phase shifter is insensitive to the polarization direction of the incident beam when polarization-insensitive AOMs are used, and no calibration is necessary.

Most importantly, one can control the required phase shifts directly by varying the phase delays between two RF signals. These properties give the method described here significant advantages over existing phase-shifting methods.

E. Li's e-mail address is enbang@uow.edu.au.

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