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Wide spectral range multiple orders and half-wave achromatic phase retarders fabricated from two lithium tantalite single crystal plates

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ABSTRACT

In a broad spectral range (300–2500 nm), we report the use of channeled spectra formed from the interference of polarized white light to extract the dispersion of the phase birefringence $\Delta n_p(\lambda)$ of the *x*- and *y*-cuts of lithium tantalite ($LiTaO_3$:LT) plates. A new method named as wavenumber difference method is used to extract the spectral behavior of the phase birefringence of the *x*- and *y*- cuts of LT plates. The correctness of the obtained birefringence data is confirmed by using Jones vector method through recalculating the plates thicknesses. The spectral variation of the phase birefringence $\Delta n_p(\lambda)$ of the *x*- and *y*-cuts of LT plates is fitted to Cauchy dispersion function with relative error for both *x*- and y-cuts of order 2.4×10^{-4}. The group birefringence dispersion $\Delta n_g(\lambda)$ of the *x*- and *y*-cuts of LT plates is also calculated and fitted to Ghosh dispersion function with relative error for both *x*- and *y*-cuts of order 2.83×10^{-4}. Furthermore, the phase retardation introduced by the *x*- and *y*-cuts of LT plates is also calculated. It is found that the amount of phase retardation confirms that the *x*- and *y*-cuts of LT plates can act as a multiple order half- and quarter-wave plates working at many different wavelengths through the spectral range 300–2500 nm. For the *x*- and *y*-cuts of LT plates, a large difference between group and phase birefringence is observed at a short wavelength (λ=300 nm); while such difference progressively diminished at longer wavelength (λ=2000 nm). In the near infrared region (NIR) region (700–2500 nm), a broad spectral full width at half maximum (FWHM) is observed for either *x*- or *y*-cut of LT plate which can act as if it is working as a zero order wave plate. Finally, an achromatic half-wave plate working at 598 nm and covering a wide spectral range (300–900 nm) is demonstrated experimentally by combining both *x*- and *y*-cuts of LT plates.

1. Introduction

Optical elements that provide phase retardation are the main components in a number of different optical systems and experiments. These optical elements are named as wave plates. Such wave plates are usually fabricated either from naturally grown birefringent crystals like calcite, quartz and mica or from synthetic grown crystals like magnesium fluoride (MgF_2) and sapphire (Al_2O_3) [1–3]. Wave plate has a wide range of applications in many fields of optics, laser and optoelectronics, such as polarization spectroscopy [3], laser modulation [4], polarization holography [5], magneto-optical measurements and fiber optics [6], ellipsometry [7], observational polarimetry [8], telecommunications [9] and recently in electronic displays technology [10]. Birefringence (Δn) of a birefringent crystals is defined as the difference between maximum (ordinary refractive index n_o) and minimum (extraordinary refractive index n_e) refractive indices. In all non cubic crystal systems, the existence of a birefringence cause phase lag equal to $\Delta\phi=\frac{2\pi}{\lambda}(n_o-n_e)t=\frac{2\pi}{\lambda}t\Delta n$ between light waves propagating along optic axes of the birefringent crystals. Wave plates are divided into multiple order, zero order and achromatic wave plates. Multiple order wave plate is used to vary the state of polarization of the light waves after passing through the plate. Polarizing devices called multiple order wave plates, either quarter or half is used to acquire various forms of light polarization depending on the phase difference introduced between light waves propagating along its two mutually perpendicular optic axes. Multiple order quarter wave plate ($\lambda/4$) is used to introduce phase difference equal to $\pi/2$ which can produce circularly polarized light from linearly polarized light and vice versa. On the other hand, multiple order half-wave plate ($\lambda/2$) is used to introduce phase difference equal to π and can produce linearly polarized light from already linearly polarized light but with different direction of vibration (polarization rotator).

For a long time, inorganic materials like mica, quartz, magnesium fluoride (MgF_2) and sapphire (Al_2O_3) are extensively used to

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fabricate wave plate [11–13]. After the recent progress achieved in the synthetic single crystal growth techniques, it is now available to grow different types of high quality single crystals. Such crystals are always in need for new inorganic birefringent synthetic single crystals to be used in wave plate fabrication in different spectral regions. One of these synthetic single crystals is LT which is a negative uniaxial crystal with $n_o > n_e$ [14]. LT is a single crystal which has a unique optical, piezoelectric and pyroelectric properties that makes it valuable member for a nonlinear optics, passive infrared sensors such as motion detectors, terahertz generation and detection, surface acoustic wave applications and cell phones. Considerable information about the physical properties of LT single crystal is available in literature [15]. In the present article, the bulk LT single crystal was grown by Czochralski method [14]. Only three plates cut along three different directions within the main bulk of LT single crystal are considered for birefringence investigation. These directions are along *x*, *y* and *z*. The *x*-, *y*- and *z*-cuts of LT single crystal plates are provided by MTI Corporation. The thicknesses of the *x*-, *y*- and *z*-cuts crystal plates are $t=0.5$ mm. The optical birefringence experiment shows that the *z*-cut plate of LT has no birefringence. On the other hand, as we will see in the experimental section both *x* and *y*-cuts have unequal birefringence spectra. In the present manuscript, the optical activity of the plates *x*-, *y*-, and *z*-cuts of LT is not investigated but it will be considered subsequently.

Previously, multiple order wave plate has been fabricated from a birefringent crystal with a plate cut so that its optic axis lies in the plane of the cut plate. On the other hand, achromatic wave plate is made-up from two wave plates of different birefringenet materials like quartz–MgF_2, gypsum–MgF_2, gypsum–KDP, gypsum–ADP and gypsum–Al_2O_3 [16–18]. Recently, a q-plate is fabricated from a thin liquid crystal material sandwiched between two specially treated glasses surfaces [19]. Such q-plate has found a number of fascinating applications in both classical and quantum photonics for example converting spin angular momentum carried by circularly polarized light beam into orbital angular momentum [20].

In the present article, our main new idea to fabricate achromatic wave plate is based on using only one birefringent material (like LT) but with two plates that have been cut along two different directions through the crystal. Therefore, the unequal birefringence dispersions of the two cut plates are equivalent of using two different birefringent materials. Consequently, to test this new idea we start with two plates of the same thicknesses ($t=0.5$ mm) cut along the *x*- and *y*-directions of the LT crystal and extracting the birefringence dispersion of these two plates using channeled spectra technique. After that, the two plates are combined together with crossed optic axes to form an achromatic wave plate working as half-wave plate at 598 nm and covering spectral range from 300 nm to 900 nm. Despite the known properties of the LT crystal, no results have been reported on using LT single crystal for wave plate fabrication and also on the use of different crystallographic planes to construct a broad spectral range achromatic wave plate. In addition, to the best of the author's knowledge, no data has been reported before on the spectral behavior of birefringence along different crystallographic planes (*x*-and *y*-cuts plates) of LT single crystal plates.

The present article deals with the practical realization of multi-order LT wave plate in the wavelength range 300–2500 nm. Also report the practical realization of wide spectral range (300–900 nm) achromatic half-wave plate working at 598 nm.

The article will be ordered as follows:

- In Section 2, the channeled spectra of the birefringent *x*- and *y*-cuts of LT plates are recorded using a spectrophotometric optical system.
- In Section 3, the birefringence dispersions of the *x*- and *y*-cuts of LT plates are extracted from the channeled spectra using the wavenumber difference method. The correctness of the obtained birefringence data is confirmed by using Jones vector method.
- In Section 4, the group birefringence dispersions are calculated for both *x*- and *y*-cuts of LT plates.
- In Section 5, the dispersions of the phase retardation are calculated for both *x*- and *y*-cuts of LT plates.
- In Section 6, the experimental realization of an achromatic half-wave plate fabricated from combining *x*- and *y*-cuts plates is presented.

2. Experimental configurations

In a wide spectral range (300–2500 nm) a double beam spectrophotometer of model JASCO V670 working in the transmission mode is used to record the transmitted polarized light $T_{Pol.}(\lambda)$ (channeled spectra) passing through either *x*-or *y*-cut of LT single crystal plate. Fig. 1 shows a schematic diagram of the optical layout used to measure the transmitted polarized light. In Fig. 1, a multi wavelength white light beam from a source S is incident normally on the front slit of a monochromator M which selects a light beam of single wavelength. Afterwards, such a beam splits via mirror S_1 into two beams of equal intensity, one is moving in the sample arm via another mirror S_2 and the other is moving into the reference arm. In the sample arm, light passes successively through polarizer P_1, a plate of LT single crystal (*x*- or *y*-cut) and analyzer A_1. In the reference arm, a polarizer P_2 and analyzer A_2 are used. The extra polarization pieces P_2 and A_2 have the role of compensating any intensity modification introduced by P_1 and A_1 in the sample arm. The intensity of the transmitted polarized light is measured via two photodetectors (D_1, D_2) by comparing the light intensities passing through the reference and sample arms. Both P and A are Glan–Thompson polarizing prisms with a ratio of the extension coefficient less than 10^{-5}. In the sample arm, a specially designed rotation mounts are used to hold and rotate P_1, A_1 and either *x*- or *y*-cut plate of LT in vertical plane. Since our aim of the present investigation is to study the spectral behavior of the birefringence of *x*- and *y*-cuts of LT single crystal plates in wide wavelength range, therefore, a careful spectral calibration of the spectrophotometer used is needed. Such calibration is performed by using three narrow band interference filters working at 334 nm, 532 nm and 1064 nm, respectively. During the measurements, the transmission axes of both P_1 and A_1 are set to a crossed position and the optic axis of either *x*- or *y*-cut of LT plate is rotated until the intensity of the transmitted light approach its maximum value ($\pm 45°$ position). In this case, the intensity of the polarized light transmitted through the *x*- or *y*-cut of LT plate is

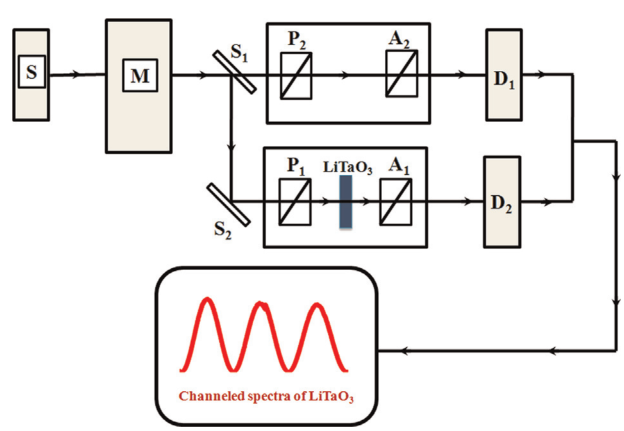

Fig. 1. Spectrophotometric arrangement used to record the channeled spectra produced from the interference of polarized white light passing through either *x*- or *y*-cut of LT plate single crystal.