Acousto-Optic Devices Based on Potassium Rare-Earth Tungstates Laser Crystals

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We present a family of original acousto-optical devices. They are based on new acousto-optical materials $K_{RE}(WO_4)_2$, where $RE = Y, Gd, Yb, Lu$. A combination of features such as radiation resistance, optical biaxiality and appreciable acousto-optical figure of merit, makes possible creation of polarization-insensitive modulator with almost 100% of diffraction efficiency. The deflector with wide angular aperture and broad range of deflection, and collinear tunable filter are also suggested.

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1. Introduction

With the progress of laser technologies, new crystalline materials are synthesized and utilized. The crystal KGd(WO$_4$)$_2$ (short: KGW) \cite{1} is one of the most famous due to a very high threshold of laser damage: up to 170 GW/cm$^2$ for $\tau = 20$ ms pulses \cite{2}. It is widely used in laser techniques as lasing material \cite{3}. Moreover, it has rather good acousto-optical (AO) properties \cite{4}, as well as the group of double potassium rare-earth tungstates $K_{RE}(WO_4)_2$, where $RE = Yb, Lu$, and also Y \cite{5, 6}. It has been demonstrated for the first time \cite{5} that their AO figure of merit $M_2$ is comparable with that of LiNbO$_3$ and better than $M_2$ of SiO$_2$, so they can efficiently replace quartz in various laser applications. Moreover, these monoclinic crystals (symmetry class $2/m$) are optically biaxial, transparent in visible and infrared ranges (0.4–5.5 $\mu$m), and demonstrate significant anisotropy.

These facts open new potentials in development of optical functional devices. First of all, basic AO devices (modulators, deflectors, tunable filters) made of these materials are able to withstand high power laser radiation, which is very important for laser industrial applications. For example, acousto-optic (AO) mode lockers for high power lasers are usually made of $\alpha$-SiO$_2$, so they require a cooling system due to high acoustic power supplied. The laser crystals $K_{RE}(WO_4)_2$ (hereafter KREW) do not need cooling as they have a higher acousto-optical efficiency. Secondly, some kind of hybrid devices can be designed, which combine laser and acousto-optic properties and provide light generation and light operation on the same crystal element.

In this paper we present three AO devices based on the KREW crystals: polarization-insensitive modulator, wide-angle deflector, and collinear tunable filter. The first device is based on isotropic (polarization-maintaining) diffraction, while the others — on anisotropic one.

2. Polarization-insensitive modulator

New AO modulator made of KGW single crystal was developed, created and tested (Fig. 1). It uses the quasi-longitudinal ultrasonic wave (QL) propagating along the axis $N_g$ of dielectric (optical) coordinate system (Fig. 2). The principle of operation is following.

![Fig. 1. Acousto-optical modulator made on KGW single crystal.](image-url)
The fact that potassium tungstates crystals $KREW$ are biaxial materials makes possible the development of new kinds of A0 units on their base, which cannot be made with use of uniaxial crystals usually utilized in acousto-optics. For example, the wide-angle deflector with wide angular aperture and great tuning range can be produced [8]. For this purpose, one must use the geometry with ultrasound wave vector being a tangent to wave surface of two modes so that non-critical phase matching condition is satisfied (Fig. 3). In this case beams with wide angular spectrum ($\Delta \theta_1$) can be diffracted efficiently while the deflection angle is proportional to acoustic frequency variation ($\Delta \theta_2 \sim \Delta K \sim \Delta f$). Such AO deflector can operate angular-extended beams, in particular, profiled laser beams, focused radiation, etc. It is useful for imaging applications. And also, the switching time of a high-speed AO modulator is approximately equal to the acoustic transit time through the waist of the focused beam $\tau = d/V ac \sim 1/\Delta \theta_1$, estimated as 20 ns and less.

\[ \Delta \theta = \frac{B \theta_1 g}{n} \]

\[ f = \frac{V_0}{\lambda} \sqrt{\left( n_2^2 - n_m^2 \right) \left( n_m^2 - n_p^2 \right) / n_m} \]

\[ n_m = 1.55 \mu m \quad n_p = 1.38 \mu m \]

\[ M_2 = 34.5 \times 10^{-15} \text{ s}^2/\text{kg} \quad V_0 = 600 \text{ m/s} \]

\[ \Delta f \sim 10^{-18} \quad \Delta K \sim 10^{-16} \]

3. Wide-angle deflector

In such a way, this deflector combines amplitude and angular effects that make new methods of the laser beam control possible. Unfortunately, this geometry of AO interaction requires quite high driving ultrasonic frequency $f$ up to a few gigahertz for visible range. The minimum velocity of shear ultrasonic waves among discussed crystals is provided by KLuW, which also demonstrates the highest acoustic anisotropy. For this crystal the driving frequencies at wavelengths 1.064 $\mu$m and 1.55 $\mu$m are 1.1 and 0.8 GHz, respectively. These rather high values can be achieved in modern AO units. In the middle infrared range the frequency is lower.

4. Collinear filter

Collinear AO interaction is always of particular attention as it provides the highest spectral resolution and the minimum driving power. For spectroscopic and imaging applications the wide angular aperture is necessary, that is why one needs to choose directions parallel to the dielectric axes $N_m$, $N_p$, and $N_g$. The most suitable acoustic
frequencies correspond to $N_y$ axis. The AOTF of this geometry (Fig. 4) is characterized with an acoustic column walk-off like the collinear AOTF on $\alpha$-SiO$_2$ [9]. Among the four discussed materials (Table), KYbW crystals can provide the best spectral resolution $\delta \lambda \sim 1/\Delta n$ because of the highest refractive index difference $\Delta n = n_p - n_m$. The bandwidth for the interaction length of 1 cm can be estimated as $\delta \lambda = 0.7$ nm. Unfortunately, the driving power cannot be calculated, because only a part of photoelastic matrix elements has been measured till now.

![Fig. 4. Schematic diagram of collinear filter on KRE(WO$_4$)$_2$ single crystal.](image)

Fig. 4. Schematic diagram of collinear filter on KRE(WO$_4$)$_2$ single crystal.

<table>
<thead>
<tr>
<th></th>
<th>$f$ [MHz]</th>
<th>$\delta \lambda$ [nm]</th>
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<tbody>
<tr>
<td>KY(WO$_4$)$_2$</td>
<td>200</td>
<td>0.76</td>
</tr>
<tr>
<td>KGD(WO$_4$)$_2$</td>
<td>150</td>
<td>1.05</td>
</tr>
<tr>
<td>KYb(WO$_4$)$_2$</td>
<td>190</td>
<td>0.74</td>
</tr>
<tr>
<td>KLu(WO$_4$)$_2$</td>
<td>170</td>
<td>0.83</td>
</tr>
</tbody>
</table>

**5. Conclusion**

The new group of acousto-optic materials, which are potassium rare-earth tungstates, possess an original complex of features: resistance to high-power laser radiation, optical biaxiality and high AO figure of merit. Therefore, a new family of AO units and devices can be created: modulators, deflectors, filters. They can provide both quantitative and qualitative advantages. New AO modulator on KGD(WO$_4$)$_2$ single crystal for non-polarized high-power light radiation was developed and tested. It demonstrated almost 100% of diffraction coefficient. Extra capabilities may probably be exhibited with implementation of anisotropic diffraction. However, the appropriate elasto-optical coefficients must be experimentally determined.

A very promising AO element developed is the deflector with wide angular aperture and broad range of deflection, which can control high-power Gaussian-profiled laser beams. It is capable to operate with more intensive laser beams than the existing TeO$_2$ modulators, requiring somewhat higher driving power, but providing an efficient modulation of arbitrary-polarized radiation.

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**References**