Over the past decade, there has been an increasing interest in Yb-doped double tungstates for laser applications. These crystals offer high emission and absorption cross sections together with a wide emission spectrum. Moreover, like in most Yb\(^{3+}\)-doped laser hosts, additional advantages are low quantum defects, relatively high doping concentrations without significant lifetime quenching, and readily available high-brightness pumping diode lasers for end pumping. As a result, efficient microcavity cw lasers [1], tunable lasers [2,3], and mode-locked lasers have been realized in monoclinic and tetragonal double tungstates [4,5]. Furthermore, the monoclinic double tungstates such as KY(WO\(_4\))\(_2\), KGd(WO\(_4\))\(_2\) (KGW), and KLu(WO\(_4\))\(_2\) have highly anisotropic optical, mechanical, and thermal properties [6,7]. The asymmetry of the ion sites gives rise to the large absorption and emission cross sections in the Yb\(^{3+}\) ion, notably for light polarized along the \(N_m\) and \(N_p\) axes of the refractive index ellipsoid. Anisotropy in the thermooptic and thermal expansion properties can be utilized for finding crystal orientations where the thermal-lensing effects are mitigated [8,9].

Monoclinic double tungstates are biaxial crystals. A beam propagating along one of the optical axes experiences internal conical refraction, an effect proposed by Hamilton already in 1832 [10]. In essence, when a circularly polarized collimated or slightly diverging Gaussian beam is launched into the crystal with a wave vector parallel to the optical axis, the Poynting vectors in the crystal form a hollow cone containing the optical axis. Thus the intensity distribution at the exit of the crystal will be a ring or rather two bright rings, separated by a Pogendorff dark ring [11], with light polarization continuously changing along the ring perimeter, as shown schematically in Fig. 1. This effect, called internal conical refraction, has been studied experimentally and theoretically by a number of authors [12–15]. As shown in [13], as the beam propagates away from the crystal the conical intensity distribution is transformed into an axial peak with surrounding weak ring structure. In this Letter we employ the conical refraction (CR) in a Yb:KGW laser crystal to achieve continuous polarization tuning in a simple cavity configuration without any additional polarizing elements in the cavity. Moreover, the laser-diode bar pumped Yb:KGW CR laser retains approximately constant efficiency for all polarization states. The output powers are comparable with those obtained in Yb:KGW cut for propagation along \(N_g\) or \(N_p\), refractive index axes.

In Yb:KGW the principal refractive indices satisfy \(N_g > N_m > N_p\). Consequently, the optical axes are located in the \(N_p-N_g\) plane. The angle between the optical axis and the \(N_g\) axis is close to 45°, slightly varying with wavelength. Two different 5% Yb:Kgd(WO\(_4\))\(_2\) (Yb:KGW) crystals with dimensions 3 mm \(\times\) 2 mm \(\times\) 3 mm were used in our experiments. The first crystal, referred to as the CR crystal, was cut for propagation along the optical axis. The crystal length along this direction was 3 mm. The other 3 mm dimension was parallel to the \(N_m\) axis. The second crystal, referred to as the NG crystal, was a reference crystal cut for beam propagation along the principal refractive index \(N_g\) axis (3 mm long), with \(N_m\) being parallel to the other 3 mm direction as in the CR crystal. Both crystals were antireflection (AR) coated for the pump and laser wavelengths.

To verify the conical refraction in CR Yb:KGW, a frequency-doubled Nd:YAG TEM\(_{00}\) single-frequency laser at 532 nm was used as the probe and was focused by a 30 mm lens to a spot size of 50 \(\mu\)m. The crystal was placed at this focus on a rotation–translation stage, making it possible to rotate the
crystal along all three axes. The semiangle, \( \alpha \), of the refraction cone inside the crystal (see Fig. 1), given by \([13]\), \( \alpha = \sqrt{(N_m - N_p)(N_g - N_{m})/N_m} \), is \( \sim 24 \text{ mrad} \). To visualize the beam distribution at the exit of the crystal, \( f = 35 \text{ mm} \) and \( f = 150 \text{ mm} \) lenses were used to obtain images on the CCD chip with approximately five times magnification. By rotating the crystal around both axes the conical refraction direction could be found. Then the typical ring or a half-ring pattern was obtained depending on the polarization of the probe beam, Fig. 2. It should be noted that, in addition to the ring pattern, the CR images also contain an axial peak, which appears when a rather strongly converging beam experiences internal conical refraction. By adjusting the polarization of the probe beam with a \( \lambda/2 \) plate, the intensity distribution in the ring can be varied, as shown in Fig. 2(a). When the power in vertical and horizontal polarizations is approximately equal, both crescents appear simultaneously. The beam direction in the crystal has to be aligned rather precisely to observe internal conical refraction patterns. This is illustrated in Fig. 2(b), where the rotation of the crystal by \( \sim 1^\circ \) around the vertical axis transforms the ring pattern to a two-dot pattern, characteristic of ordinary double refraction. In this measurement the powers in vertical and horizontal polarizations were approximately equal.

For the laser experiments, the laser crystal was wrapped in indium foil and mounted in a copper holder that was held at constant temperature by circulating water. The plane-parallel input coupler was AR coated for the pump wavelength and high-reflection coated for 1000–1200 nm. The output coupler was concave output coupler in a single, say horizontal, direction the cavity feedback can be established for only one of the corresponding polarizations or for an arbitrary mixture of polarizations without additional cavity realignment. Figure 3 shows output power and degree of polarization as a function of the mirror translation distance. The diameter of the internal conical refraction ring at the exit surface of the 3 mm crystal is \( \sim 145 \text{ \mu m} \). This is in reasonable agreement with the experimental result that a mirror translation of \( \sim 90 \text{ \mu m} \) is necessary for a complete rotation of the polarization. This measurement was performed at full pump power. At lower powers the necessary translation distances decrease as misalignment loss has more impact. In comparison, mirror translation for the NG crystal only implies power drop.

It is important to realize that the gain–loss balance stays the same when the polarization state is changed. That means that the effective gain for light polarized along the \( N_m \) direction, \( \beta \sigma_m^e - (1-\beta)\sigma_m^a \), is equal to the effective gain for the perpendicular polarization, \( 0.5(\beta(\sigma_g^e + \sigma_p^a) - (1-\beta)(\sigma_g^a + \sigma_p^e)) \), where \( \sigma, \beta \) denote cross sections at the laser wavelength and population inversion ratio, respectively. Superscripts \( a \) and \( e \) signify absorption and emission, while subscripts attribute the cross sections to appropriate refractive index axes. Obviously, because of anisotropy, to maintain the same effective gain in the crystal, the reabsorption loss has to adjust when polarization is tuned. For the same pumping rate, this can happen by laser adjusting its wavelength. Indeed, for the laser output polarized along the \( N_m \) direction the out-

![Fig. 2. (Color online) (a) CCD camera pictures of the probe beam transverse profile at the end facet of the crystal for different polarizations of the probe beam when propagating along the CR direction. (b) Pictures for a constant polarization when the crystal is rotated around the vertical axis.](image)

![Fig. 3. (Color online) Output powers and degrees of polarization at different mirror positions for a typical pair of polarization directions.](image)
put wavelength was 1036 nm, while for the orthogonal direction the wavelength was 1038 nm. The intermediate polarizations showed intermediate wavelengths. The FWHM spectral bandwidth was ~0.5 nm in all cases.

The laser with reference NG crystal in an analogous cavity generated linearly polarized output polarized along the $N_p$ direction. The output wavelength was 1041 nm with a FWHM of 0.5 nm. Even though the $N_m$ direction shows a larger emission cross section than the $N_p$ direction at the cross-section peak wavelength of ~1025 nm, it also has larger reabsorption loss. Thus for longer wavelengths, $\beta\sigma^m_p - (1-\beta)\sigma^m_m > \beta\sigma^p_p - (1-\beta)\sigma^p_m$, and $N_p$ polarization will start lasing first.

The laser output powers as a function of incident pump power obtained in the lasers using NG and CR crystals are shown in Fig. 4. It is clear that the slope efficiencies are approximately the same, so there should be no additional losses introduced in the CR crystal. The threshold, however, is higher in this crystal. The slope efficiency and the output power obtained in this laser are approximately the same as obtained in a reference, standard, $N_p$- or $N_g$-cut Yb:KGW crystal. The maximum output power achieved was 8.6 W with a slope efficiency of 60.5% with respect to incident pump power. This approach to polarization control should be applicable to all biaxial laser host materials with different dopants. This is also an effective method to achieve unpolarized output from highly anisotropic media. For example, this is to our knowledge the first completely unpolarized laser in Yb-doped, ordered double tungstates. Further improvement of the extinction ratio could be possible by increasing the diameter of the conical refraction ring by using a longer crystal. By replacing the mirror translation as the cavity alignment discriminator with a fast electro-optical or electromechanical component, it should be possible to use this method for high-speed polarization control as well.

In conclusion, we have demonstrated an Yb:KGW laser where the polarization direction, as well as the extinction ratio, can be arbitrarily changed. This is, to the best of our knowledge, the first laser employing gain material in the direction of conical refraction. Since the method for altering the polarization is based on conical refraction in the laser crystal, there is no need for any additional cavity elements. The slope efficiency and the output power obtained in this laser are approximately the same as obtained in a reference, standard, $N_p$- or $N_g$-cut Yb:KGW crystal. The maximum output power achieved was 8.6 W with a slope efficiency of 60.5% with respect to incident pump power. This approach to polarization control should be applicable to all biaxial laser host materials with different dopants. This is also an effective method to achieve unpolarized output from highly anisotropic media. For example, this is to our knowledge the first completely unpolarized laser in Yb-doped, ordered double tungstates. Further improvement of the extinction ratio could be possible by increasing the diameter of the conical refraction ring by using a longer crystal. By replacing the mirror translation as the cavity alignment discriminator with a fast electro-optical or electromechanical component, it should be possible to use this method for high-speed polarization control as well.

References