Mirror coatings for eye-safe laser generation

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Abstract. Eye-safety is of paramount importance in the use of laser-based instruments. Eye-safe output at 1.54 micron is very important for various applications such as robot vision, range finding and laser radars in civil and military use. Nonlinear crystals have been used in state-of-the-art rangefinders for providing eye-safe output in the 1550 ± 50 nm band. We present our results on designing a back and a front mirror for eye-safe laser generation at a wavelength of 1538 nm. The back mirror is designed for high transmission at 1067 nm and high reflection at 1351 and 1538 nm. The front mirror is designed for high transmission at 1067 nm, high reflection at 1351 nm and partial reflection at 1538 nm. The optimized design is achieved using titanium dioxide and silicon dioxide layers. In the experiment, the coatings are fabricated by electron beam evaporation on BK7 glass substrates. The characteristics of the coated samples are compared with the results of the calculations, showing good correspondence. The laser mirrors so prepared passed the laser damage and durability tests.

1. Introduction

"Eye safe" lasers are very important for different applications in optical communications and lidar techniques.

Eye hazards caused by laser radiation depend on the wavelength, laser power, exposure time and type of tissue. Excessive exposure to visible radiation causes photochemical and thermal retina damage. According to the American standard ANSI Z136.1-1986, the wavelength of 1.5 µm is treated as safe for direct eye exposure to the beam for energy densities 100 times larger than for 10.6 µm (CO₂ laser) and 2×10⁵ times larger than for 1.06 µm (Nd:YAG laser). According to the standards developed by International Electrotechnical Committee, the application of laser devices that do not satisfy the safety requirements will be soon considerably limited.

At present, the methods developed of eye protection against laser radiation have to do with the application of "eye-safe" lasers that emit radiation outside the spectral transmission region of eye, i.e. outside the range 400-1400 nm.

The rapid development of Raman-active media has made stimulated Raman scattering (SRS) in crystals a promising method for wavelength conversion of laser radiation [1-3]. One especially interesting approach among the SRS systems is the self-stimulated Raman laser that achieves laser emission and SRS action in one crystal.

In the past few years, all-solid-state self-stimulated Raman lasers have been reported in materials such as Nd:KGD(WO₄)₂ [4,5], Nd: PbWO₄ [6], Yb:KGd(WO₄)₂ [7] and Yb:KY(WO₄)₂ [8].
The KGd(WO₄)₂ (KGW) crystal is popular for optically active components due to its suitability as a rare-earth host material, its high third-order nonlinear susceptibility, high thermal conductivity, and strong Raman conversion properties. KGW has prominent Raman modes at 768 and 901 cm⁻¹ arising from the tungsten-oxygen sublattice in the crystal which are useful for wavelength conversion in the near infrared spectrum [9]. Compact and efficient lasers have been constructed using passive resonator Q-switching [10-14]. In this case, the laser mirrors are common for all elements and must cover the spectral requirements for several spectral lines.

In this paper we report the design and fabrication of back and front (output) mirrors coatings on BK7 glass substrate to be used for self-stimulated Raman laser generation in Nd:KGW Various specifications of back and front mirrors were found in the scientific literature and in the technical catalogues. The back mirror should have high transmission at the wavelength 1067 nm, together with high reflection at the lasing wavelength 1351 nm and at the SRS wavelength 1538 nm. For the front mirror one needs high transmission at the wavelength 1067 nm; high reflection at the lasing wavelength 1351 nm and partial reflection (about 30±10%) at the SRS wavelength 1538 nm for extracting a portion of the energy through the mirror. High transmission of both mirrors at 1067 nm is necessary to prevent lasing at this wavelength and promote lasing at 1351 nm used for SRS conversion to 1538 nm.

2. Results and discussion
Optimization with different starting number of layers and specified transmission (reflection) at the wavelengths of interest is performed using the software package TFCalc (Spectra Software, Inc). The selection of the coating materials is based on their refractive index values, physical stability characteristics, their transparency in the desired wavelength regions and interface compatibility. The commonly used high index coating materials are TiO₂, Ta₂O₅, HfO₂, ZrO₂ and the low index coating material is SiO₂. TiO₂ is chosen as a high index and SiO₂, as a low index coating material since this combination has a maximum refractive index difference and yields the widest high-reflection zone. Increasing the number of layers increases the cumulative stress and sometimes limits the efficiency of the device. Random errors in the deposited layer thicknesses lead to discrepancies between the calculated and the implemented spectral characteristics. Therefore, it is better to use a minimum number of layers in the design. The characteristics desired (transmission/reflection) were designed by optimizing the thicknesses of the high and low refractive index layers. The refractive indices and dispersions of the materials used were determined beforehand and used in the optimization. The starting designs were mirrors at a reference wavelength of 1450 nm with different number of layers (between 15 and 30). The reflectivity desired at each wavelength of choice was added as discrete targets and the respective thickness optimization was carried out. Appropriate sensitivity and yield analysis was then carried out to check the feasibility of the solutions obtained. The optimized design was achieved with seventeen and nineteen layers of alternate layers of TiO₂ and SiO₂ for the back and front mirror, respectively.

The mirror coatings were fabricated by using electron-beam gun evaporation system in a Leybold A700QE vacuum coating unit. Local high absorption generally occurs due to the loss of film stoichiometry and can be minimized by depositing the film in an oxygen atmosphere. Initially, the system is evacuated to a vacuum better than 5×10⁻⁶ mbar. The evaporation took place at the working vacuum of 5×10⁻⁵ mbar for SiO₂ and 3.5×10⁻⁴ mbar for TiO₂. The rate of evaporation in the case of SiO₂ was 0.8 nm/s and 0.4 nm/s for TiO₂. The thicknesses of the layers were controlled by a quartz microbalance system Inficon XTC-2. The sample holders were fixed to a dome that was rotated with respect to the central point of the coating chamber for better uniformity. The substrate temperature during deposition was maintained at 300°C within a tolerance of ±10°C.

The theoretically designed index profile for the back mirror is given in figure 1; the corresponding transmittance curve (dashed line) is given in figure 2. As shown in figure 2, the theoretically achieved transmission is 99.8% at 1067 nm, 0.33% at 1351 nm (the lasing wavelength) and 0.38% at 1538 nm (SRS wavelength). Similarly, the theoretical index profile for the front mirror is given in figure 3,
while the corresponding design transmittance is given in figure 4 (dashed line). As is evident from figure 4, the theoretically achieved transmission is 99.5% at 1067 nm, 1.0% at 1538 nm and 70% at 1538 nm.

The experimental results for the back and the front mirrors are also shown in figure 2 and figure 4 (solid lines) (as measured by a Perkin-Elmer Lambda 950 spectrophotometer). The achieved transmission for the back mirror is $T=97.9\%$ at 1067, $T=0.38\%$ at 1351 and $T=0.34\%$ at 1538 nm. The experimentally measured transmittance of the front mirror is $T=97.5\%$ at 1067, $T=1.2\%$ at 1351 and $T=67\%$ at 1538 nm.

The theoretical and experimental transmission curves are in close agreement. There are, however, some discrepancies in the experimentally achieved transmission values compared to the theoretical values due to the absorption and scattering losses of the columnar microstructure and to the dispersion of the coating materials deposited. At 1067 nm, the transmittance measured depends also on the quality of the AR coating on the second surface of the BK glass substrate.

The coated samples were tested to withstand five 10 ns pulses of 1500 MW/cm$^2$ laser radiation at 1067 nm in a single point. The samples are tested for repeatability of the characteristics and durability in view of regular commercial production. The coated samples passed the adhesion and abrasion tests.

3. Conclusion
We designed and fabricated back and front (output) mirrors for eye-safe self-stimulated Raman laser generation in a Nd:KGW passively Q-switched intracavity Raman laser. Laser mirrors are common for all laser elements and must cover the requirements for three spectral lines simultaneously. The optimized designs were achieved with a minimum number of layers in order to avoid cumulative stress and errors in fabrication. The spectral characteristics of the samples fabricated were compared with the results of the calculations, showing good correspondence. In preliminary experiments with such a Raman laser, pulses with 30-ns duration and 8-mJ energy were generated.
Acknowledgments
The experiments are carried out in the frame of a research project between ISSP-BAS and “Optix” Co., Panagyurishte. We acknowledge the contribution of “Optix” Co. team for manufacturing and testing the samples.

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