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SIMPLE DESIGN OF DOUBLE-LAYER ANTIREFLECTION COATING FOR Er-DOPED GLASS LASER APPLICATION

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Abstract. *In an Erbium-doped glass laser resonator, parasitic light oscillations (yielding a lowering of the output laser beam power) may be avoided by deposition of well-adapted antireflection coatings on the edges of the active glass medium. However, for laser application, efficient double - layers are scarce in the literature. Here, we propose a simple design of double-layer (total thickness* < 490 *nm) composed of thin films of* MgF_2 *and* Al_2O_3*, materials that are easy to deposit by electron beam evaporation. Such coating design allows a calculated reflectance to be lower than 0.01% in the considered 1530-1570 nm near-infrared range.*

Keywords: lasers; erbium-doped glass; antireflection coatings; thin films; refractive index.

Classification numbers: 42.79.Wc; 73.50.Rb; 78.20.Ci.

I. INTRODUCTION

As soon as the lasing effect was first detected in Erbium-doped glasses in 1965, specialists turned their attention towards trying to achieve a suitable laser spectral range allowing both eye safety and easy detection by room-temperature photodetectors [1]. Thus, many Er-doped glass lasers provide now a useful coherent source in the spectral range of around 1.5 μm: such wavelength is eye-safe [2], and convenient for many applications, such as lidar and range measurements, fiber-optic communication, free-space optical communications, remote sensing, wind mapping, laser surgery, and range finding [3, 4].

The operational principle of the Erbium glass laser is illustrated in Fig. 1. The heart of the laser is an active medium (often in the shape of a rod) made of glass, which can be doped with ions such as Er^+, Yb^+, or Cr^+.

When ions of the active material are excited by a pumping source (flash lamp or laser diode), they absorb photons coming from the pump source and then re-emit photons that are in the 1.5 μm wavelength region. This generated light is progressively amplified, by going back and forth many times, through the glass rod and reflected by two mirrors in an optical resonator. One of the mirrors is partially transmissive (Fig. 1 right), yielding an output laser beam. Internal reflections at the boundaries of the active medium can lead to parasitic oscillations, which will decrease the energy available for laser radiation [5]. Such a drawback can be avoided or minimized by applying antireflection (AR) coatings on both sides of the glass rod.

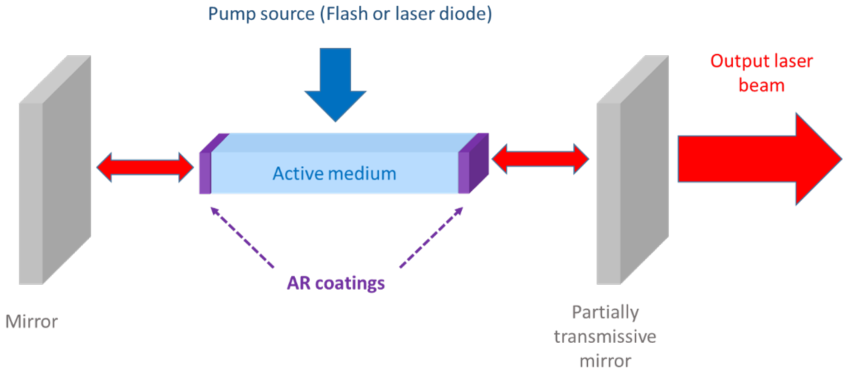

Fig. 1. (Color online) Schematic view of an Erbium glass laser. In the active medium (blue-colored), the ions absorb photons coming from the pump source, and re-emit light (around 1.5 μm wavelength), which is amplified between two mirrors of a resonator (in gray). AR coatings deposited at the edges of the active medium allow minimizing parasitic oscillations which decrease the energy available for laser radiation [5].

To build an AR coating, the simplest method consists in depositing on the surface of the active medium (considered as a substrate of refractive index n_S) a single layer whose refractive index n_1 is equal to $\sqrt{n_S}$. Hence, taking $n_S \approx 1.50$ (many glasses have a refractive index close to this value), the AR coating shall satisfy $n_1 \approx 1.22$. Meeting this condition is difficult since transparent materials with such low n1 value are hardly available. Thus, a concept of "effective medium" may be employed [6], through the elaboration of porous or nanostructured films, which have an average lower refractive index. However, the cost of fabrication of such unconventional AR coatings remains an obstacle to real applications [7].

On the other hand, conventional AR coatings composed of two or more uniform layers are much easier to elaborate, more robust mechanically, and more stable in time than nanostructured coatings. However, a high number of layers implies a high number of interfaces, which are usually initiators of Laser Induced Damage (LID) [8]. Thus, to minimize LID, the number of conventional layers to deposit shall be kept to a minimum (preferably 2 or 3 layers). The overall problem to solve consists in determining all the parameters of the desired AR coating (the number of layers, the refractive index n_i, and the thickness di of each layer). Specifically, in the case of a double-layer system (which may better minimize LID), the most widespread mathematical method involves the use of quarter-wave layers [9]. In this case, two materials have first to be chosen carefully (which is the first difficulty to overcome), so that their real refractive indices n_1 (corresponding to the inner layer in contact with the substrate) and n_2 (corresponding to the top layer) may satisfy (as best as possible) the following index condition, to obtain a (narrow-band) "V-shaped" coating [10]:

$$\frac{n_2}{n_1} = \frac{1}{\sqrt{n_S}}. \tag{1}$$

Once the two materials are chosen, the thicknesses of the quarter-wave layers can be directly deduced (through $n_1.d_1 = n_2.d_2 = \lambda/4$) to give zero reflectance at the desired central wavelength λ. However, such a method does generally not lead to the most optimal thickness values, hence further numerical optimization has to be undertaken (second problem).

At present, towards laser application, the objective of AR coatings (for Nd:Lasers [5, 11], Er:Lasers [5]) is to reduce the reflectance below 0.2%, which is a mean value often taken as reference by laser optics suppliers [12, 13]. However, efficient double-layer coating designs proposed that allow reflectance lower than 0.2% in the Near-Infrared region are rare in literature [14, 15]. Hereafter, we report a simple design of efficient AR double-layer coating for Erbium-doped glass, which yields a calculated reflectance below 0.01% [16] in the [1.53-1.57 μm] range. Moreover, such design involves thin films of MgF_2 and Al_2O_3, which are materials easy to deposit.

II. METHOD AND EXPERIMENT

II.1. Determination of the refractive index n_S of the Er-glass substrate

To find well-adapted AR coatings that match the Er-glass substrate, the refractive index n_S of the substrate must first be determined with sufficient precision, otherwise the AR coating may not be efficient enough. For instance, a design optimized for $n_S = 1.51$ will be very different for $n_S = 1.54$ (see Fig. 2).

The refractive index of the substrate must therefore be determined to the second decimal place. To such a goal, a convenient spectrophotometric method consists in measuring the transmittances (T_1 and T_2) of two samples (of different thicknesses d_1 and d_2) of the same material. A simple analytical method published recently [17] allows then the derivation of the optical parameters (k_S, n_S) of the substrate from the (T_1, T_2) experimental data. In our case, samples have been prepared with thicknesses $d_1 = 2.80$ mm and $d_2 = 34.98$ mm, for which FTIR (Fourier-transform Infrared Spectroscopy) measurements are easy to carry out. Transmittances $T_1(\lambda)$ and $T_2(\lambda)$ of the two samples, measured by a Nicolet^{TM} iS50 FTIR Spectrometer (Thermoscientific), are shown in the [1.53-1.57 μm] range (Fig. 3).

From the transmittance data, the extinction coefficient k_S and the refractive index n_S of the Er-glass substrate are easily determined, using analytical expressions [17]. The evolution of k_S and n_S is shown in Fig. 4. It can be observed that k_S decreases slightly ($k_S \approx 3.6 \times 10^{-6}$ at 1.55 μm), whereas n_S stays rather constant: $n_S \approx 1.54$. This refractive index value will be taken into account for the design of the AR coating.

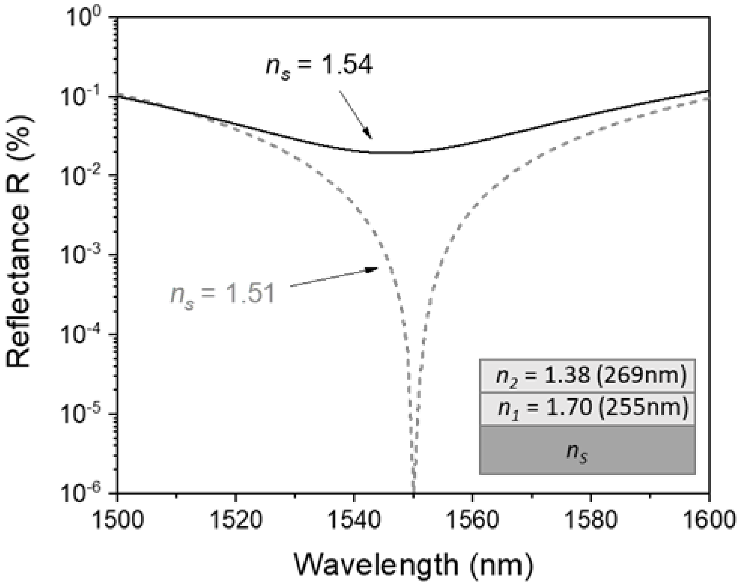

Fig. 2. Reflectance (design shown in the inset) which has been optimized for $n_S = 1.51$ (dashed gray curve) and reflectance of the same design for $n_S = 1.54$ (black curve).

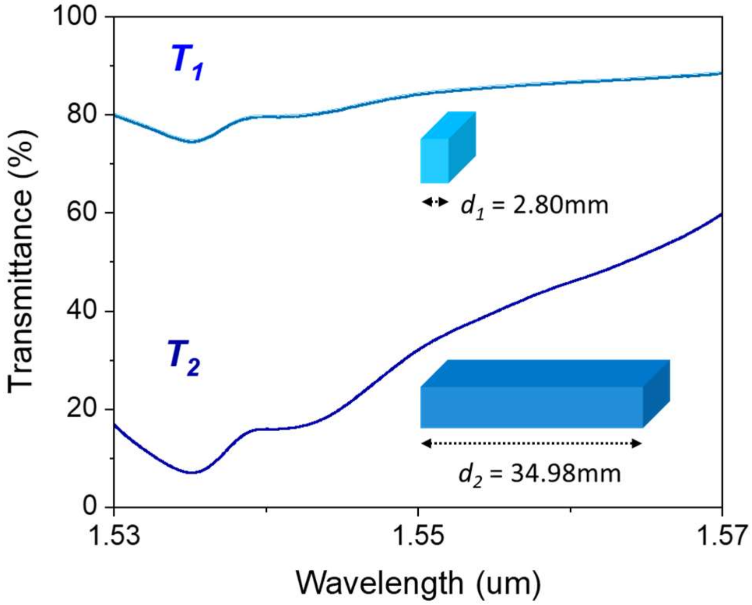

Fig. 3. Transmittances measured by FTIR, of the two samples, in the [1.53-1.57 μm] wavelength range.

From these (k,n) values, the reflectance coefficient R of the Er-glass substrate (of thickness d2) can be calculated by using the following exact analytical expressions [18]:

$$R = Ri + \frac{Ri.Ti^2.\exp(-2\alpha.d_2)}{1-Ri^2.\exp(-2\alpha.d_2)} \text{ with } Ri = \frac{(n-1)^2+k^2}{(n+1)^2+k^2}, Ti = 1-Ri, \text{ and } \alpha = (4\pi.k)/\lambda \quad (2)$$

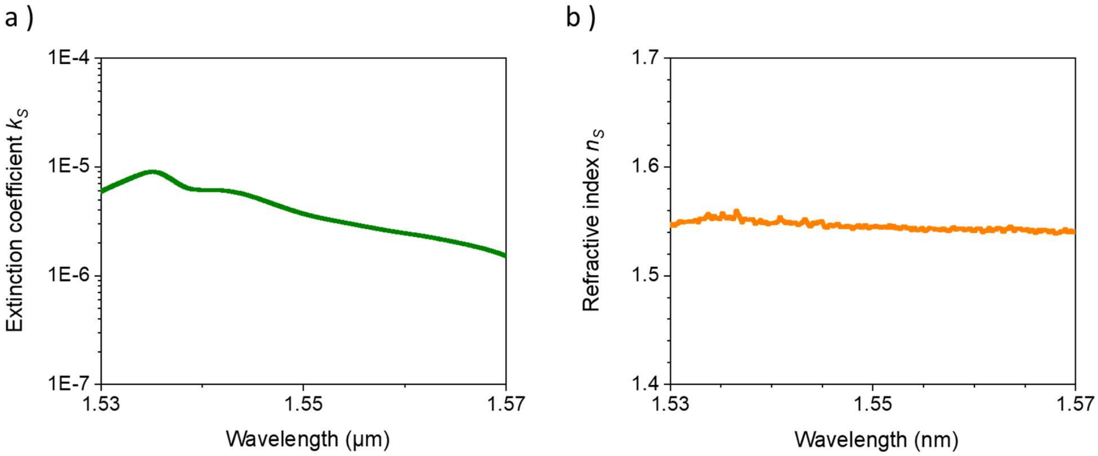

Fig. 4. Optical parameters of the Er-glass substrate: a) Extinction coefficient k_S, b) Refractive index n_S.

Hence, for $\lambda = 1.55$ μm, we have $R \approx 5.05\%$, which is much higher than 0.2%. Thus, to reduce drastically R, deposition of an AR coating on the edges of the active medium is required.

II.2. Design of the double-layer AR coating for the Er-glass substrate

In the case of laser systems, AR coatings allow avoiding parasitic oscillations which lower the available output beam power (Fig. 1). To minimize LID, we focus here only on double-layer coating designs. On the whole, for multilayer (including double-layer) AR coatings, there exists a large number of refractive index combinations which yield zero reflectance at one wavelength. Among all the mathematical solutions, one of the most well-known methods involves the use of quarter-wave layers. In such a case, satisfying Eq. (1) allows obtaining a narrow-band V-coating. Since $n_S = 1.54$, this implies that n1 and n2 are such that:

$$\frac{n_2}{n_1} = \frac{1}{n_S} \approx 0.806. \tag{3}$$

In the near-infrared region, various double-layer AR coating designs have been proposed for laser applications, namely: TiO_2 $(n_1 \approx 2.45)$ and Al_2O_3 $(n_2 \approx 1.65)$ [14], HfO_2 $(n_1 \approx 1.98)$ and Al_2O_3 $(n_2 \approx 1.65)$ [15] and Nb_2O_5 $(n_1 \approx 2.20)$ and SiO_2 $(n_2 \approx 1.47)$ [16].

For the TiO_2-Al_2O_3 design, $n_2/n_1 \approx 0.673$ is not very close to 0.806, this is also the case for Nb_2O_5-SiO_2 $(n_2/n_1 \approx 0.668)$. For HfO_2-Al_2O_3, $n_2/n_1 \approx 0.833$, which is much closer to the target value. But HfO_2 is usually deposited using ALD (Atomic Layer Deposition) [15] which is less easy to carry out than electron-beam (EB) evaporation or thermal evaporation. That is why we propose a new design of double-layer coating (to be deposited on both sides of the substrate) that involves Al_2O_3 and MgF_2. Indeed, Al_2O_3, suitable as AR coating for laser erbium glasses [19–21], can be deposited by EB evaporation and has a refractive index of $n_1 \approx 1.65$ at 1.55 μm [21]. Using carefully the same deposition means as in Ref. [21] may allow obtaining such a refractive index value. Concerning MgF_2, thin films deposited on glass by EB evaporation have already been characterized by transmission methods [22]. We found that the refractive index of MgF_2

is $n_2 \approx 1.32$ at 1.55 μm. Thus for such a combination, $n_2/n_1 \approx 0.800$, which is very close to 0.806. The next step consists in determining the thicknesses of the two layers. The first design (in Table 1, Design 1) corresponds to quarter-wave layers. The second design (Design 2) corresponds to thicknesses that have been optimized numerically: d_1 and d_2 varied both in the [0-600 nm] range, and the minimum reflectance was obtained for a specific (d_1, d_2) combination.

Table 1. Designs proposed, involving Al_2O_3/MgF_2 coatings.

Design	Layers	Materials	Refractive index	Thickness (nm)
Design 1	Substrate	Glass	1.54	-
	layer1	Al_2O_3	1.65	235
	layer2	MgF_2	1.32	293
Design 2	Substrate	Glass	1.54	-
	layer1	Al_2O_3	1.65	178
	layer2	MgF_2	1.32	309

II.3. Results and discussion

The calculated spectra of the residual reflectance (using matrix theory [8]) are shown in Fig. 5. It can be observed that Design 1 (total thickness = 528 nm) allows the reflectance to be lower than 0.1% in the 1500-1600 nm range: it is even lower than 0.02% in the 1530-1570 nm interval (Fig. 5a).

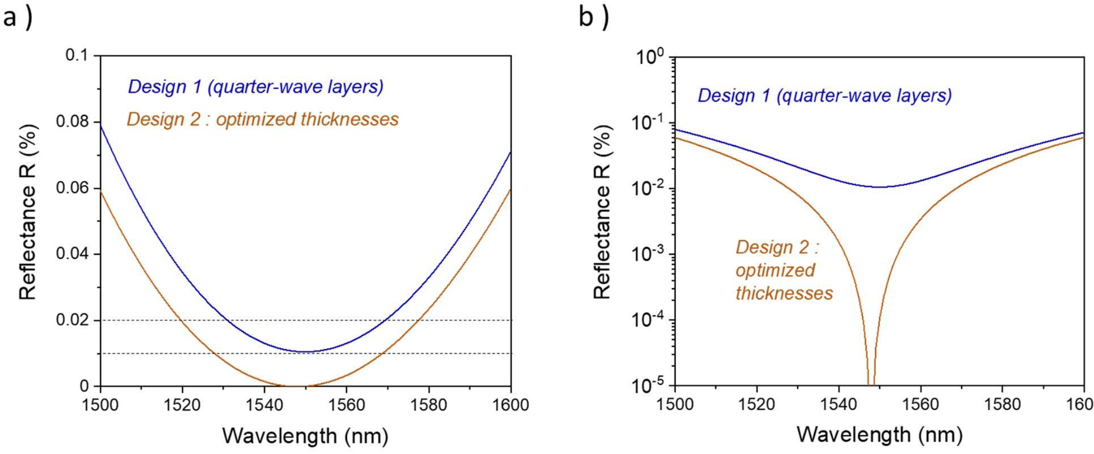

Fig. 5. Calculated reflectance of the two designs a) with a linear vertical scale b) using a logarithmic vertical scale.

Design 2, which involves a total thickness of 487 nm (lower than Design 1) appears more efficient than Design 1, with a reflectance lower than 0.01% in the 1530-1570 nm range. Hence, such a simple AR coating configuration, which involves only two layers and a low total thickness (< 490 nm), appears highly interesting to implement, the more so as the materials (Al_2O_3 and MgF_2) are easy to elaborate by EB deposition.

III. CONCLUSION

In this paper, a simple design of double-layer AR coating for Erbium-doped glass laser application has been presented. First, the refractive index of the erbium glass substrate has been determined precisely ($n_S = 1.54$). Then, two materials (Al_2O_3 and MgF_2) have been proposed, since they are easy to deposit, and their refractive indices allow a mathematical condition (involving quarter-waver layers) to be well satisfied. The thicknesses of the two layers have been determined by numerical optimization. The total thickness of the AR coating (< 490 nm) is low and allows the calculated reflectance to be lower than 0.01% in the [1.53-1.57 μm] range. Besides, future experimental elaboration of such coating design may result in a slightly higher experimental reflectance, which may however remain well beneath 0.2% (value often mentioned as reference).

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