Theory and Measuring of Antireflection Coatings

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The characterization of antireflection (AR) coatings is not trivial. A preferred measurement method is the Hakki-Paoli method. But for broad-area lasers, an advanced method has to be used. One way is the measurement of the spectrally resolved far field, another is the use of single-mode ridge-waveguide lasers. Different AR coatings in the range of 10^{-1}–10^{-4} *(fabricated by ion-beam sputter deposition) have been deposited on single-mode lasers and characterized successfully.*

1. Introduction

Antireflection (AR) coatings with reflectivities lower than 10^{-4} are required for many applications such as laser amplifiers. These coatings can be deposited by reactive ion-beam sputter deposition [1] to achieve the required reflectivities with low absorption and a good passivation of the semiconductor material. The measurement of antireflection coatings with reflectivities below $R < 10^{-2}$ is not trivial.

2. Measurement Methods

A quick and simple method to determine the reflectivity of a coating on a laser facet is the threshold-shift method [1]. The L–I curve is measured before and after the deposition of the coating. The threshold current increases with decreasing reflectivity, see Fig. 1.

$$R^* = R \left(\frac{I_{\mathrm{th}}}{I^*_{\mathrm{th}}} \right)^{2L\Gamma g_0} . \tag{1}$$

Whereas R^* is the reflectivity of the coated facet, which can be calculated from the threshold currents of the uncoated I_{th} and the coated I^*_{th} lasers. For this calculations, the laser length L, the gain Γg_0, and the effective refractive index n_{eff} have to be known. The reflectivity R of the uncoated laser is $R = \left(\frac{1-n_{\mathrm{eff}}}{1+n_{\mathrm{eff}}} \right)^2$. Using this method, high-reflection (HR) coatings can also be measured. If the parameters of the uncoated laser are not known, the reflectivity can be determined with an advanced method described in [2]. Using this threshold-shift method, antireflection coatings with reflectivities up to $R \geq 10^{-3}$ can be measured. For lower reflectivities, no threshold can be found and this method cannot be used.

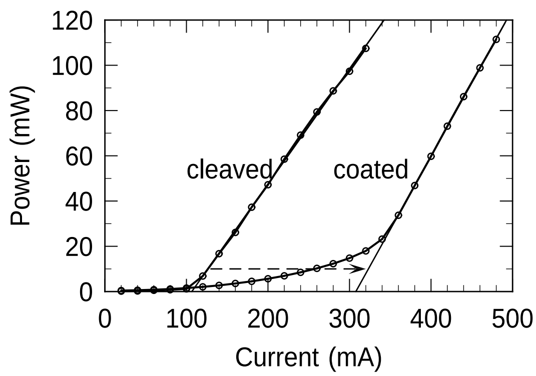

Fig. 1: Threshold-shift method; With decreasing reflectivity R the threshold current I_{th} increases.

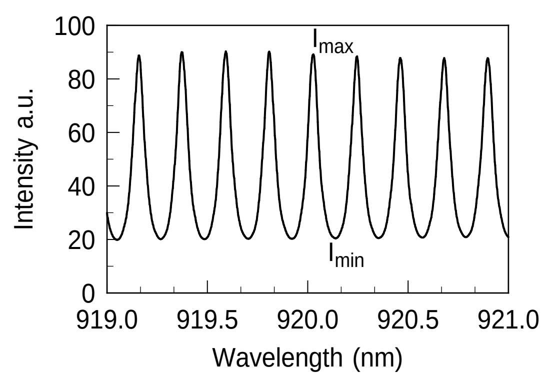

Fig. 2: Hakki-Paoli (Kaminow-Eisenstein) method; Modulation of the intensity I over wavelength λ.

For low reflectivities, the Kaminow-Eisenstein method [3] which is based on Hakki-Paoli [4] is a method commonly used for the determination of the reflectivity. The coated laser is operated with the current corresponding to the threshold current of the uncoated laser. With a spectrometer, the modulation of the intensity over wavelength is measured (see Fig. 2) and with

$$m = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \; , \qquad m = \frac{2a}{1+a^2} \; , \text{ and} \qquad R^* = a^2 R_1 \tag{2}$$

the reflectivity R^* can be calculated. The effective refractive index n_{eff} has to be known to calculate the reflectivity R of the uncoated laser. For broad area lasers when a simple optic is used to couple the light directly into a spectrometer, the spectral modulation and so the calculated reflectivity is too low. The reason is the difference in the spectrum for different propagation angles. This will be discussed in the next section.

3. Theory

In a laser, there are modes with different propagation angles. Assuming single mode behavior in the vertical (y) direction, there are different propagation angles in the lateral (x) direction. The laser length L is orientated in (z) direction.

3.1 Simulation

In Fig. 3, the $k_{\text{x}}/k_{\text{z}}$ diagram for a laser with a length of $L_{\text{z}} = 500\,\mu\text{m}$ and a width of $L_{\text{x}} = 100\,\mu\text{m}$ is shown.

$$k = \sqrt{(nk_{\text{x}})^2 + (nk_{\text{z}})^2} = \frac{2\pi n}{\lambda} \quad \text{and} \qquad k_{\text{x,z}} = \frac{\pi n}{L_{\text{x,z}}} \,. \tag{3}$$

The solutions of constructive superposition are given which results in an intensity maximum in the spectrum are shown as points in the k_x/k_z diagram in Fig. 3. It can be seen that the distance in the longitudinal (z) direction is shorter than in the lateral (x) direction due to the larger length than the width. With increasing angle (increasing k_x) and consistent longitudinal mode (k_z), the absolute value of k increases. This results in a decreasing wavelength. Figure 4 shows the expected form for the spectrally resolved far field. The points demonstrate maxima in the spectrum which shift towards shorter wavelengths with increasing propagation angle.

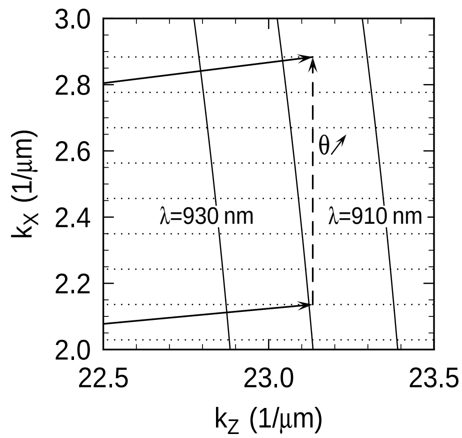

Fig. 3: k_x/k_z diagram of a laser with a length of $L_z = 500\,\mu$m and a width of $L_x = 100\,\mu$m.

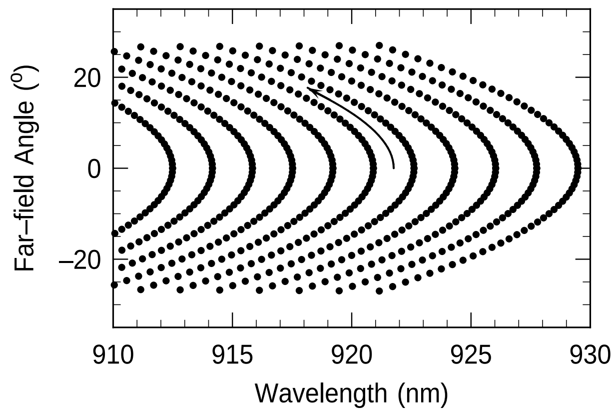

Fig. 4: Simulation of a spectrally resolved far field for a laser with a length of $L_z = 500\,\mu$m and a width of $L_x = 100\,\mu$m.

In Fig. 5, the k_x/k_z diagram for a laser with a length of $L_z = 500\,\mu$m and a width of $L_x = 4\,\mu$m is shown.

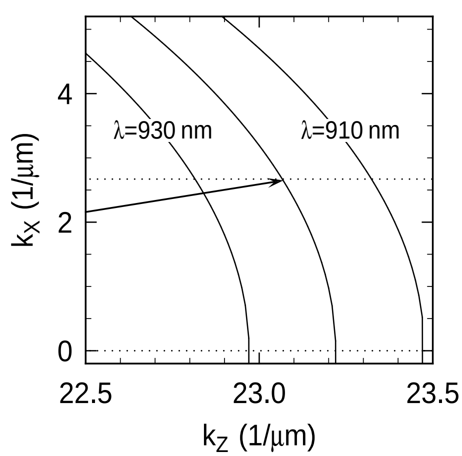

Fig. 5: k_x/k_z diagram of a laser with a length of $L_z = 500\,\mu$m and a width of $L_x = 4\,\mu$m.

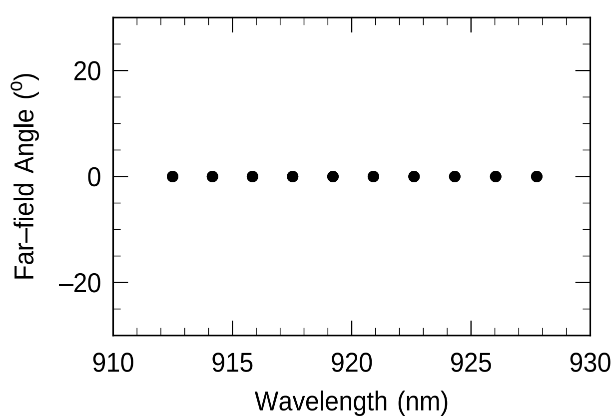

Fig. 6: Simulation of a spectrally resolved far field for a laser with a length of $L_z = 500\,\mu$m and a width of $L_x = 4\,\mu$m.

In this case, the distance of the points in the k_x direction is much larger due to the small laser width. This results in a different spectrally resolved far field compared to that of the laser with 100 μm width. Spectral maxima are only expected at an angle of 0° as shown in Fig. 6.

3.2 Measurement

The measurement of the spectrally resolved far field is described in [5] and depicted in Fig. 7. The laser beam is collimated in the vertical direction and focused into the spectrometer. Due to the astigmatism, the horizontal direction shows a focus behind the first collimating lens (corrected far field) which is magnified with a cylindrical lens.

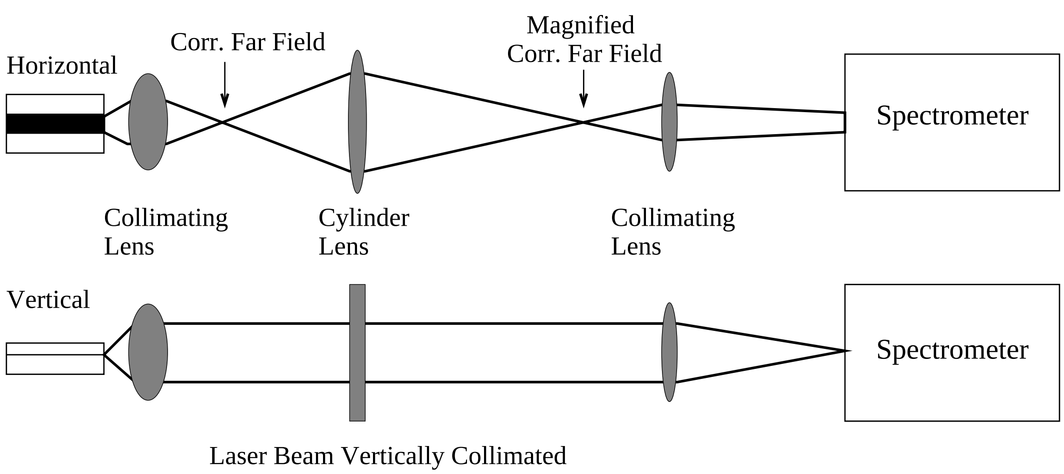

Fig. 7: Measurement setup for the spectrally resolved far field.

Figure 8 shows the measured results for a ridge-waveguide laser with a ridge width of 100 μm at an emission wavelength of $\lambda = 920$ nm. The picture shows the intensity over wavelength and far-field angle. The spectrum has the same shape as the simulation in Fig. 4, with increasing far-field angle, the maxima in the intensity shift to shorter wavelengths. In Fig. 9, the spectrally resolved far field of a ridge-waveguide laser with a ridge width of 4 μm is shown. As shown in the simulation (Fig. 6), only maxima around the far-field angle of 0° can be observed.

Using a spectrally resolved far field, the modulation at one angle can be measured correctly. However, if the entire laser beam is coupled into a spectrometer without filtering out all angles other than that of 0°, the resulting modulation is too low. With increasing angle, the spectrum shifts to shorter wavelengths. Hence, the spectrometer superposes all spectra of the different angles and the resulting spectrum shows lower maxima and higher minima which results in a lower modulation depth and so in lower reflectivities. As the laser width is increased, the apparent calculated reflectivity is lowered.

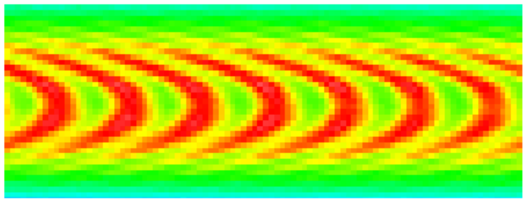

Fig. 8: Spectrally resolved far field of a ridge-waveguide laser with a ridge width of 100 μm.

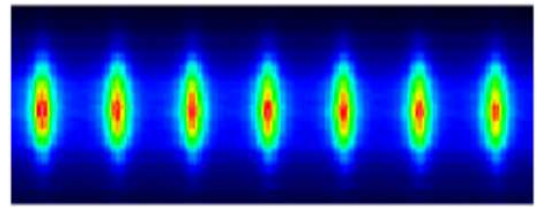

Fig. 9: Spectrally resolved far field of a ridge-waveguide laser with a ridge width of 4 μm.

4. Results

Ridge-waveguide lasers with different ridge widths have been fabricated [6]. After the deposition of antireflection coatings on one facet (fabricated by ion-beam sputter deposition), the light has been coupled into a spectrometer. Using the modulation of the spectrum, the reflectivity is calculated using Eqn. 2. In Fig. 10, the measured reflectivities for three different AR coatings over ridge width is shown. As expected, the reflectivity decreases with increasing laser width. In the range of laser widths between 3 μm and 6 μm, the reflectivities show the values of the designed reflectivities.

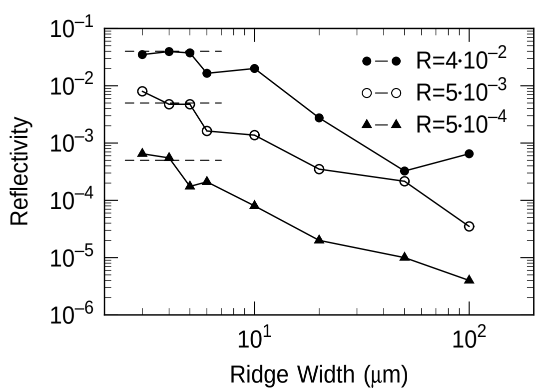

Fig. 10: Reflectivity over ridge width measured with the Hakki-Paoli method.

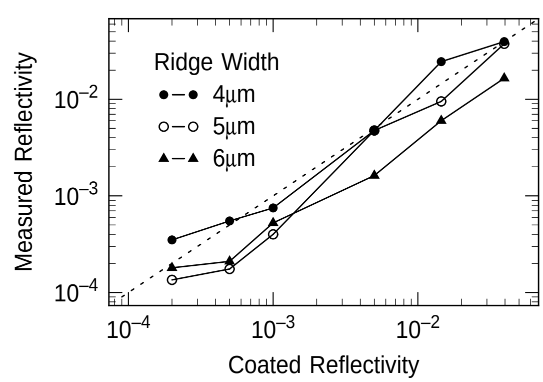

Fig. 11: Calculated and measured reflectivities for different laser widths measured with the Hakki-Paoli method.

Different AR coatings in the range of 10^{-1} to 10^{-4} have been fabricated and measured. In Fig. 11, the results for laser widths between 4 μm and 6 μm are shown. As can be seen, the measured values are in the range of the designed reflectivities. This demonstrates that the reflectivities of AR coatings on ridge-waveguide lasers with small ridge widths can be accurately characterized using the Hakki-Paoli method.

5. Conclusion

Different antireflection coatings have been deposited on ridge-waveguide lasers with ion-beam sputter deposition. Using the Hakki-Paoli method, the reflectivities have been measured. For ridge widths in the range of $4\,\mu$m to $6\,\mu$m, the results are quite good. With such a measurement method, a fast and correct characterization of AR coatings is possible.

References

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