Epitaxial Bragg Mirrors with Broad Omnidirectional Stop Band in the Mid-Infrared

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We present laser-quality low-loss Bragg mirrors exhibiting a broad omnidirectional stop band in the mid-infrared around 6.9 µm. Due to the high refractive index contrast of 80%, Bragg mirrors made from only three layer pairs of PbTe and EuTe are demonstrated to achieve reflectances higher than 99 % for angles of incidence up to 40° and higher than 98% for angles of incidence up to 70°. The relative omnidirectional stop band width is 50%.

Introduction

Similar to metallic mirrors, omnidirectional Bragg reflectors offer high reflectivity independent of the angle of incidence, but combined with the low-loss behavior and transparency of dielectric multilayer stacks. Such devices are advantageous for applications in laser resonators where light is incident from oblique directions, as in low-loss ring resonators or in two-dimensional planar-mirror resonators. They enable also the realization of highly-efficient corner-cube retro reflectors. Bragg mirrors exhibiting omnidirectional stop bands in the mid-infrared were demonstrated both theoretically and experimentally with relative stop band widths up to 45 % [1].

In our work, a high-finesse microcavity formed by two omnidirectional PbTe/EuTe Bragg mirrors for the mid-infrared was used for detailed optical analysis of the mirror properties. The appearance of a cavity resonance facilitates the accurate determination of the mirror reflectance from the quality factor of the resonator [2]. Similar mirrors have successfully been used for cw operating mid-infrared vertical-cavity surface-emitting lasers with divergence angles of 1° [3].

Theory

In modeling the transmittance behavior of a half wavelength microcavity enclosed between Bragg mirrors the characteristic matrix description is preferred [4], because it provides insight into the energetic position and extent of the photonic band gap.

An omnidirectional Bragg mirror will remain reflective throughout all angles of incidence, whenever the refractive indices of the environment and the mirror dielectrics are such that light impinging at grazing incidence will be refracted strong enough to avoid the Brewster angle on all subsequent refractions (Fig. 1 (d)). For a given microcavity structure (Fig. 1 (b)), the simulated angular dependence of the transmittance spectra (Fig. 1 (e), (f)) displays the stopband of almost vanishing transmission, lined by the Fabry-Perot interference fringes of the microcavity structure as a whole. Figs. 1 (c), (d) show the calculated photonic band structure of the Bragg mirrors forming the cavity.

The finesse F_m of a Fabry-Perot resonator of order m can be expressed as (Fig. 1 (a); R is the geometrical mean of the reflectances of the enclosing mirrors):

$$\frac{1}{m}\frac{k_0}{FWHM(k_0)} = F_m \approx \pi\frac{\sqrt{R}}{1-R}$$

Therefore, reflectances that are derived from the resonance line width FWHM (k_0) will always provide a worst-case estimate for the reflectance of one mirror.

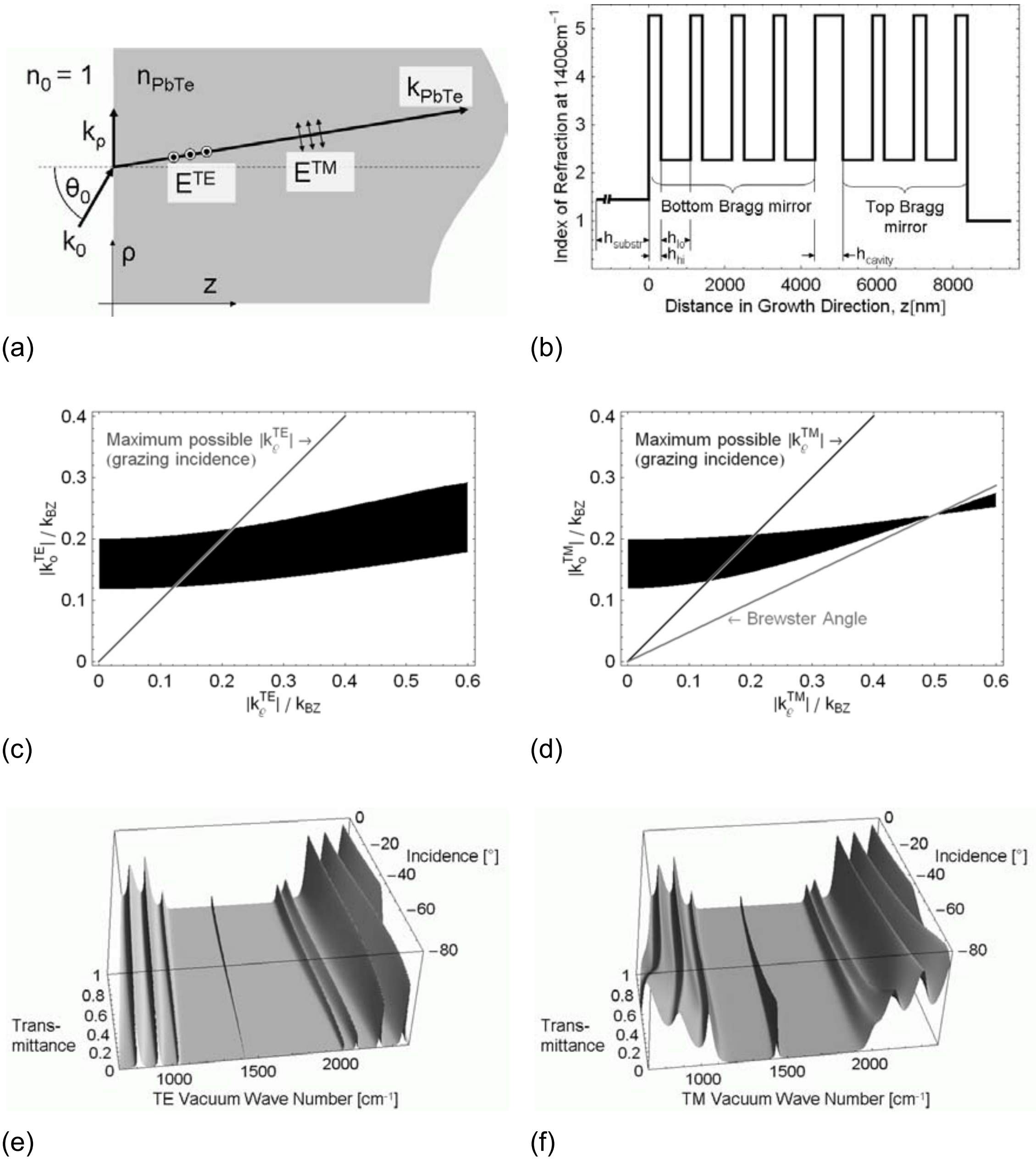

Fig. 1: (a) Terminology and coordinate system used; (b) target microcavity structure by index of refraction of its components; (c) and (d): Calculated angular dependence of the stopband width (black) for one of the mirrors as described in Fig. 1(b). By expressing the angle of incidence in terms of the in-plane wave vector component kρ (Fig. 1(a)) the angle dependence is transformed into a dispersion relation $\omega(k_\rho) = c_0 k_0(k_\rho)$. $k_{BZ} \equiv 2\pi/(h_{lo}+h_{hi})$. The region below the light line (grazing incidence) corresponds to unphysical system states. (e), (f): Angular dependence of calculated transmittance spectra for the model structure (b).

Experimental

Sample Preparation

On a ‹111› BaF_2 substrate the half wave cavity structure targeted at a wavelength of 6.9 µm was grown by molecular beam epitaxy. As indicated in Fig. 1 (b), the overall structure consisted of four PbTe/EuTe mirror layer pairs of width h_{hi} = 317 nm and h_{lo} = 777 nm respectively, a PbTe cavity layer of width h_{cavity} = 732 nm and three top mirror layer pairs. With the special choice of materials, even at grazing incidence all angles of refraction within the mirror structure will remain smaller than the Brewster angle for TM polarized light (Fig. 1 (d)).

Measurements and Results

The angular dependence of the transmittance spectrum was determined by Fourier transform infrared (FTIR) spectroscopy. Probing the sample through a 2 mm aperture made a compromise over the need for a large aperture to proceed to high angles of incidence and the desire to measure the true resonance line width by avoiding the influence of lateral sample inhomogeneities. From the Lorentzian shaped resonance of the 0° spectrum through a pinhole aperture and through the 2 mm aperture an apparatus function was calculated, which afterwards was used to deconvolve the resonance line shapes of the angle scan with the 2 mm aperture (see insert in Fig. 2 (b)).

In Fig. 2 (a) the angular dependence of the stop band edges (triangles) and the resonance position (squares) are plotted. Theoretical predictions made by matrix methods (lines) are evidently in good agreement to the experimental findings. At 3% transmittance level a broad omnidirectional stopband of 727 cm^{-1} width around a center frequency of 1440 cm^{-1} could be found. This corresponds to a relative omnidirectional stopband width of 50%.

In Fig. 2(b) the angular dependence of the halfwidth of the resonance linewidth is plotted for TE, TM polarization. Taking into account the penetration of the light into the mirrors, an effective cavity finesse (Fig. 2 (c)) of well over 100 for angles of incidence up to 70° can be deduced from this. The lower limit mirror reflectance data in Fig. 2 (d) clearly show reflectances higher than 99% for angles of incidence up to 40° and higher than 98% for angles of incidence up to 70°.

Conclusion

By means of an epitaxially fabricated half-wave microcavity for the mid-infrared formed by Bragg mirror layers made from PbTe and EuTe, we have experimentally and theoretically demonstrated the omnidirectionality of these Bragg mirrors for angles of incidence up to 70°. Around 6.9 µm, we have achieved a relative stopband width of 50% and have demonstrated effective reflectances higher than 99% for angles up to 40° and higher than 98% for angles of incidence up to 70°, indicating the suitability for laser applications.

Acknowledgements

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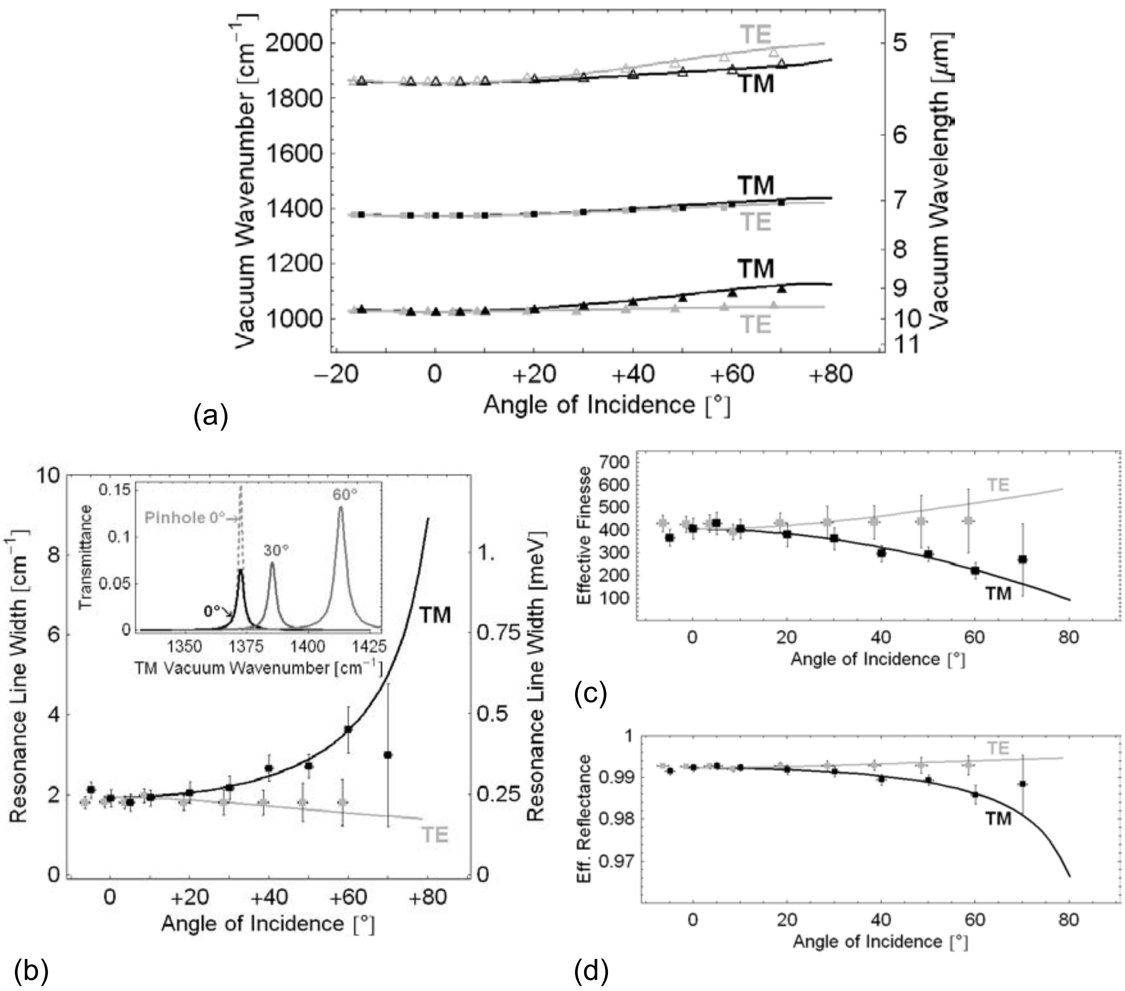

Fig. 2: (a) Angular dependence of Bragg mirror stopband edge (triangles) and cavity resonance (squares) position, compared to model prediction (lines). (b) Experimentally determined TE, TM resonance line widths. Insert: Angle scan TM resonance line shapes compared to that measured through a pinhole aperture (dashed line). (c) Effective finesse of the microcavity, as derived from the effective order of the cavity resonance and its line width. (d) Angular dependence of the lower limit of the effective Bragg mirror reflectance, as deduced from (c).

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