Review

Epitaxial Bragg mirrors for the mid-infrared and their applications

W. Heiss\textsuperscript{a,}\textsuperscript{*}, T. Schwarzl\textsuperscript{a}, J. Roither\textsuperscript{a}, G. Springholz\textsuperscript{a}, M. Aigle\textsuperscript{b}, H. Pascher\textsuperscript{b}, K. Biermann\textsuperscript{c}, K. Reimann\textsuperscript{c}

\textsuperscript{a} Institut für Halbleiter- und Festkörperphysik, Universität Linz, Altenbergerstraße 69, A-4020 Linz, Austria
\textsuperscript{b} Experimentalphysik I, Universität Bayreuth, Universitätstr. 30, D-95447 Bayreuth, Germany
\textsuperscript{c} Max-Born-Institut für Nichtlineare Optik and Kurzzeitspektroskopie, D-12489 Berlin, Germany

Abstract

Bragg interference mirrors consisting of stacks of dielectric layers with an optical thickness of a quarter wavelength are of great importance for optoelectronic device applications. For the mid-infrared spectral range mirrors with high reflectivity stop bands are fabricated from combinations of Pb\textsubscript{1-x}Eu\textsubscript{x}Te/EuTe materials by molecular beam epitaxy on BaF\textsubscript{2} substrates. These mirrors designed by the transfer matrix method exhibit reflectivities in excess of 99\% by only 3 Bragg mirror layer pairs and very wide stop band regions, reaching a width of up to 60\% of the target wavelength. Based on these very efficient mirrors, planar microcavities are demonstrated with an ultra-high effective finesse of up to 1700. Stimulated emission between 3 and 6\,\mu m is obtained by optically pumping a vertical-cavity surface-emitting laser containing PbTe quantum wells with Pb\textsubscript{1-x}Eu\textsubscript{x}Te barriers as active medium embedded between two dielectric Bragg mirrors. Depending on the design of the resonator, pulsed laser operation is observed up to 65\,\degree C. The enhancement of light absorption in the cavity is used to study the absorption of superlattices containing correlated self-organized PbSe quantum dots. © 2002 Elsevier Science Ltd. All rights reserved.

Abbreviations: Molecular beam epitaxy (MBE); Vertical-cavity surface-emitting laser (VCSEL); Resonant-cavity light-emitting diode (RCLED); Mid-infrared (MIR); Fourier transform infrared (FTIR); Full-width at half-maximum (FWHM); Scanning electron micrograph (SEM); Fabry–Perot resonator (FPR); Quantum well (QW)

*Corresponding author. Tel.: +43-732-2468-9643; fax: +43-732-2468-9696.
E-mail address: wolfgang.heiss@jk.uni-linz.ac.at (W. Heiss).
1. Introduction

Bragg mirrors are multilayer structures consisting of alternating pairs of two dielectric materials with different refractive indices. By using such stacks of layers, mirrors can be tailored to obtain any reflectivity between 0% and almost 100% for a specific target wavelength \( \lambda_T \). Unlike the case of metallic mirrors, where the high reflectivity arises due to extinction of light, Bragg mirrors exhibit small intrinsic absorption. The high reflectivity is purely caused by multiple-interference effects. The small absorption losses together with the large variety of accessible reflectivities make Bragg-type reflectors very attractive for optical and optoelectronic devices. While combinations of dielectric layers giving vanishing reflectivities are widely used for antireflection coatings, dielectric multilayers with high reflectivity are mainly used as mirrors for laser applications.

The prerequisites for achieving highly efficient Bragg mirrors are (1) dielectric layers with high purity to prevent absorption in the layers, (2) smooth surfaces and interfaces to avoid light scattering, and (3) the precise control of layer thicknesses to match the mirrors to the required target wavelength. Therefore, vacuum thin film deposition techniques such as thermal evaporation or electron beam deposition are usually employed for industrial applications. By these methods, polycrystalline films are usually obtained for which the refractive index depends not only on the chosen material but also on the molecular packing density in the thin film. Although, the latter can be increased by ion bombardment of the films during deposition, which leads to an increase of the refractive index, superior mechanical and optical properties can be obtained by the growth of single-crystalline epitaxial layers. Dielectric films with the highest crystalline quality and purity are currently obtained by molecular beam epitaxy (MBE), allowing the controlled deposition of a large variety of materials.

Epitaxial Bragg mirrors of single-crystalline layers are particularly important because they can be integrated in optoelectronic semiconductor devices. For such
purposes, the electronically active part of the device can be grown on top of a buried epitaxial Bragg mirror, or even in between two mirrors forming a resonator structure. Examples of such devices are vertical-cavity surface-emitting lasers (VCSEL) [1–3], resonant-cavity light-emitting diodes (RCLED) [4–6], solar cells with enhanced efficiency [7], wavelength selective photodetectors [8–10], or Fabry–Perot filters [11] and reflection modulators [12,13]. These devices benefit either from the intensity enhancement of electromagnetic waves within the active medium of the optical resonator formed by the two parallel Bragg mirrors, or from the fact that optical resonators only support certain wavelengths (cavity modes), so that they act as spectral and spatial filters. Both effects are used in lasers with vertical cavities to obtain monomode operation with output beams whose profile and divergence are much better than that from conventional, lateral-emitting diode lasers. Whereas in lasers the cavity modes are used for light amplification, for Fabry–Perot detectors and solar cells the absorption of light in the active layers is enhanced leading to higher sensitivity and efficiency at the resonance wavelength [7–10]. The enhancement of absorption within cavity modes is also used in Fabry–Perot reflection modulators [12,13]. In these devices, e.g., the quantum-confined Stark effect is applied to tune by an electric field the fundamental absorption edge of a quantum well from energies above a cavity mode (no absorption at the mode) into the cavity mode. This leads to a reduction of the reflectivity at the energy of the cavity mode, with field-off to field-on reflectivity contrasts of the order of 15 dB [14]. Electric fields can not only be used to modulate the absorption of the active layer, but can also be applied to change the reflectivity of the Bragg mirrors itself. Electro-optical modulation of the Bragg mirror reflectivity was demonstrated to be a tool to control the cavity-loss of VCSELs [15] and was shown to be more efficient at high frequencies than the conventional control by current modulation in doped mirror layers [15,16]. This modulation of the mirror reflectivity offers an additional possibility to control electro-optical devices based on Fabry–Perot resonators.

Recently, vertical resonators consisting of two mirrors separated by a distance of the order of the wavelength of the light have attracted tremendous interest due to their unique physical properties and their high potential for device applications [17]. These so called microcavities exhibit interesting quantum-optical effects like the appearance of cavity polaritons. Thus, in microcavities the “vacuum-field Rabi splitting”, known from atomic physics was observed due to the coupling of confined photons with the electronic states of the cavity medium [18]. Furthermore, in microcavity devices competing modes can be suppressed, opening up the possibility to achieve monomode thresholdless semiconductor lasers [19]. In microcavities, the spontaneous emission can be either inhibited or enhanced [20], which is used to improve efficiencies in RCLEDs [21]. Light-emitting diodes with record external quantum efficiencies around 20% were obtained by designing the resonant cavity by compromising directionality and spectral width of the cavity mode [21].

The present review describes the design of dielectric Bragg interference mirrors, their fabrication by molecular beam epitaxy, and their characterization by optical
spectroscopy. Furthermore, several examples for applications of Bragg mirrors are discussed in detail. Most available opto-electronic devices are fabricated from III–V and II–VI semiconductors for the visible and near infrared spectral range. In contrast, this work focuses on mirrors based on narrow-band-gap IV–VI semiconductor (lead salt) compounds and their applications for mid-infrared (MIR) devices. Lead salts exhibit nearly symmetric conduction and valence bands at the direct energy band gap and up to two orders of magnitude lower Auger recombination rates than in InSb or Hg_{1-x}Cd_xTe with comparable values for the energy bandgap [22,23]. For infrared emitters, IV–VI ternary alloys with elements like Eu, Sr, and Mn have been applied because of their large tunability of the energy gaps even for low concentrations of these elements. As a result of their favorable properties, PbSe/Pb_{1-x}Sr_xSe MIR laser diodes were demonstrated to operate in a pulsed mode up to a temperature of 60°C [24] whereas CW operation is obtained in PbTe/Pb_{1-x}Eu_xSe_yTe_{1-y} separate-confinement buried heterostructure lasers up to 223 K [22]. This represents the highest CW operation temperature for electrically pumped MIR interband diode lasers.

Since the entire spectral region between 3 and 30 μm, that includes the absorption bands of almost all polyatomic molecular species of practical interest is covered by lead-salt laser diodes, these devices are most commonly used for measurements in laser spectrometers [26–29] and for gas spectroscopy applications [30], for measuring the position and intensity of trace gas absorption lines [31]. Such lead salt diode laser spectrometers have been used in fundamental research, e.g., to study the pressure broadening [32] and the line-shift coefficients of NO_2 [33] and different isotopomers of CO [34], and to investigate the intensity and self-broadening of SO_2 [35]. Lead salt diode-based gas analyzers are, however, also applied for more practical purposes like monitoring gaseous pollutants such as CO, NH_3 and CH_4 in open atmosphere [36] over distances of several 100 m. Furthermore, lead salt diode laser spectrometers can be used for medical diagnostics by analyzing exhaled air. From the ratio of ^13C to ^12C isotopes in urea breath tests, e.g., *Helicobacter Pylori* bacteria can be detected [37]. Detection of endogenous NO and CO in breath by using lead salt diode laser spectrometers could also be used as an indicator of diseases as well as a measure of therapy efficiencies, since these oxides reflect the state of many important systems in organisms. Lead salt diode lasers are also applied in tunable heterodyne receivers as local oscillators [38]. By using the sun as light source, such heterodyne receivers are used, e.g., for measuring the total amount and distribution of ozone in heights between 15 and 40 km [38].

2. Bragg mirror design

2.1. Principle and simulation procedure

The high reflectivity of Bragg mirrors is caused by constructive interference of electromagnetic waves reflected at the consecutive interfaces of a multilayer structure. To obtain constructive interference, all interfaces have to be parallel,
and, depending on the refractive indices of the media surrounding the Bragg mirror, the distance between subsequent interfaces should be an even or odd multiple of one quarter of the optical wavelength $\lambda$. In practice, stacks of two alternating layers with different refractive indices $n_1$ and $n_2$ and with a thickness equal to a quarter optical wavelength are used. The mirror characteristics are then governed by the refractive index contrast $n_1/n_2$ and the number of $\lambda/4$ pairs $N$. At the target wavelength, the reflectivity $R$ of a Bragg mirror consisting of $N\lambda/4$ layers is given by:

$$R = \left( \frac{1 - n_t/n_i(n_1/n_2)^{2N}}{1 + n_t/n_i(n_1/n_2)^{2N}} \right)^2,$$

where $n_i$ and $n_t$ are the refractive indices of the materials in front of and behind the multilayer stack. Eq. (1) shows clearly that apart from the refractive index contrast between the mirror materials the reflectivity is determined by the total number $N$ of layers as well as by the refractive indices $n_i$ and $n_t$ outside the mirror. This is especially relevant when Bragg mirrors are integrated in electro-optical devices, where light is generated within active layers with $n \gg 1$.

While Eq. (1) gives the value for the maximum reflectivity at the target wavelength, in the following, we briefly discuss the transfer matrix method [39–41], which allows the calculation of the whole transmission and reflectivity spectrum of an arbitrary arrangement of dielectric layers. Within this method, the relation between the electric field of the incident light $E_I$, the reflected light $E_R$, and the transmitted light $E_T$ is given by the scattering matrix $S$:

$$\begin{pmatrix} E_I \\ E_R \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_T \\ 0 \end{pmatrix}. \quad (2)$$

$S$ is a product of the a series of matrices $M_{ij}$ and $D_j (S = M_{01}D_1M_{12}D_2 \ldots D_NM_{NS})$, where the $M_{ij}$ matrices describe the reflection and transmission at a single interface,

$$M_{ij} = \frac{1}{t_{ij}} \begin{pmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{pmatrix}, \quad (3)$$

and the $D$ matrices account for the phase shift

$$\Delta \Phi_j = \frac{2\pi n_j}{\lambda} \cos \Theta_j d_j, \quad D_j = \begin{pmatrix} e^{-i\Delta \Phi_j} & 0 \\ 0 & e^{+i\Delta \Phi_j} \end{pmatrix} \quad (4)$$

of the electromagnetic wave traveling through a layer with the thickness $d_j$ and with and angle of incidence $\Theta_j$. The $M_{ij}$ matrices contain the angle dependent Fresnel equations, which are different for the two polarizations parallel and perpendicular to the surface of the multilayer:

$$t_{ij}^{\perp(1)} = \frac{2n_i \cos \Theta_i}{n_{i(j)} \cos \Theta_i + n_{j(i)} \cos \Theta_j},$$

$$r_{ij}^{\perp(1)} = \frac{n_{i(j)} \cos \Theta_i - n_{j(i)} \cos \Theta_j}{n_{i(j)} \cos \Theta_i + n_{j(i)} \cos \Theta_j}. \quad (5)$$
The transmission $T$ and the reflectivity $R$ of the whole structure is then directly given by the components of the scattering matrix:

$$T = \frac{\text{Re}(n_1)}{\text{Re}(n_i)} \frac{|1/S_{11}|^2}{1}, \quad R = |S_{21}/S_{11}|^2.$$ \hfill (6)

By the use of the transfer matrix formalism, the dispersion of the Bragg mirror reflectivity $R(\lambda)$ can be obtained from Eq. (6) by numerically calculating the scattering matrix $S(\lambda)$. Alternatively, $R(\lambda)$ can be calculated for perpendicular incidence of light by analytical methods based on the coupled mode equations. As a result, the reflection coefficient of a Bragg mirror of thickness $l$ consisting of Bragg layer pairs with alternating indices $n_1$ and $n_2$ is approximated by [42]:

$$r = \exp \left( -\frac{2\pi}{\Lambda} (z - z_{12}) \right) \frac{-\kappa \sinh(\Gamma l)}{\Gamma \cosh(\Gamma l) - i\delta \sinh(\Gamma l)},$$ \hfill (7)

where $\Lambda = d_1 + d_2$ is the periodicity of the layer pairs, $\kappa = 2(n_1 - n_2)/\lambda$ is the coupling coefficient, $\Gamma = \sqrt{\kappa^2 - \delta^2}$ is the propagation constant in the Bragg medium, and $\delta = \tilde{n}2\pi/\lambda + iz - \pi/\Lambda$ is the detuning parameter. $\tilde{n}$ in turn is the averaged refractive index defined as $\Lambda \tilde{n} = d_1 n_1 + d_2 n_2$, $z$ is the absorption coefficient, $z$ is the coordinate in growth direction and $z_{12}$ denotes the position of an arbitrary interface between a low and high refractive index material. Eq. (7) only yields accurate results if the difference of the refractive indices of the layers is not too large. Furthermore, Eq. (7) is not correct because it neglects the interface between the multilayer stack and the substrate as well as the topmost interface with air [42]. In the following, we therefore exclusively use the numerical transfer matrix method for the design of the Bragg mirrors, which has the additional advantage that by the same method the reflectivity and transmission spectra of arbitrary stacks of layers can be predicted.

2.2. Numerical results of several Bragg mirror structures

As an example, the calculated reflectivity spectra of a dielectric mirror with 4 Bragg layer pairs are shown in Fig. 1, where the refractive index of BaF$_2$ of $n = 1.4$ was used as low refractive index material and the high refractive index $n_2$ was arbitrarily set equal to 2, 3 and 4. For all three values of $n_2$, the reflectivity spectra show a clear Bragg mirror stop band around the chosen target wavelength of 1 $\mu$m. With increasing $n_2$, not only the maximum reflectivity increases as predicted by Eq. (1), but also the width of the mirror stop band increases dramatically. Outside the stop band region Fabry–Perot fringes appear due to multiple reflections at the mirror surface and the mirror-substrate interface where the substrate material was also set to BaF$_2$. Fig. 2 shows the maximum reflectivity and the stop band width as a function of the relative refractive index contrast $n_{\text{rel}} = (n_1 - n_2)/(n_1 + n_2)$ in detail. For mirrors with 4 Bragg layer pairs, a relative refractive index contrast of 0.275 is necessary to obtain a reflectivity higher than 99\%, whereas with 8 layer pairs for the same refractive index contrast a reflectivity of 99.99\% is obtained. While the reflectivity shows a strongly nonlinear dependence on $n_{\text{rel}}$, the relative stop band
width, on the other hand, in which the reflectivity is higher than 90%, increases almost linearly with increasing $n_{rel}$. As shown in Fig. 2, the width of the stop band is almost independent of the number of Bragg mirror pairs and it reaches values up to $0.9 \times \lambda_T$ for $n_{rel} = 0.55$. 

Fig. 1. Reflectivity spectra of a Bragg mirror with 4 layer pairs calculated for a target wavelength of 1 μm and a refractive index of $n_2 = 2, 3, 4$ for the high index $\lambda/4$ layer and an refractive index of $n_1 = 1.4$ for the low index $\lambda/4$ layer (equal to BaF$_2$).

Fig. 2. Left axis: Calculated reflectivity at the target wavelength of 1 μm as a function of the relative refractive index contrast $n_{rel} = (n_2 - n_1)/(n_2 + n_1)$ calculated for a mirror with 4 (solid line) and 8 (dashed dotted line) Bragg layer pairs with $n_1 = 1.4$. Right axis: Reflectivity stop band width normalized by the target wavelength versus relative refractive index contrast.
For many applications, where the electrical properties of the dielectric materials are crucial for the device performance, the refractive index contrast is often limited to values of the order of 10%. With such a low $n_{\text{rel}}$ about 30 layer pairs are required to achieve sufficiently high reflectivities for laser resonators. In this case, it is worthwhile to use hybrid structures of dielectric and metallic mirrors, which allow to reduce the number of required layer pairs and thus to reduce the total device thickness [43]. Whereas highest reflectivities are obtained by using Ag, Al or Au metal layers on top of the dielectric stacks, sometimes even the choice of the metallic material is restricted, e.g., when the metallization should be used as electrical contact or as etching mask. In Fig. 3, the calculated reflectivity of a Pb$_{0.99}$Eu$_{0.01}$Te/ Pb$_{0.94}$Eu$_{0.06}$Te Bragg mirror with Cr on top is presented as an example. For the optical constants of the metal layer, tabulated values for the target energy of 1570 cm$^{-1}$ and a temperature of 20 K were used ($n = 6.5$ and $\kappa = 25$) [44]. This mirror is intended to be used on top of a laser device in which PbTe is the light emitting material. Therefore, in Fig. 3 the calculated reflectivity at the mirror target photon energy is shown as a function of the number of layer pairs for incidence of light from PbTe as active medium. Starting from $R = 80\%$ intrinsic reflectivity for the pure metal from PbTe without any Bragg layers (given by the low contrast of the real part of the refractive index between PbTe ($n = 6$) and Cr ($n = 6.5$)), a rapid increase in reflectivity with increasing numbers of Bragg layer pairs is observed. The significant improvement of the Bragg mirror pairs due to the metal layer is evident. For more than 25 layer pairs, however, the Bragg interference reflection is so high that the Cr topmost layer does not yield a difference anymore. On the other hand, to achieve 98% reflectivity the required number of layer pairs can be reduced from 29 to 20 with the metal layer. In addition, the stop band width becomes larger with the
metal layer, as can be seen from the inset in Fig. 3 that shows the actual reflectivity spectrum for a ten-period mirror with and without a Cr cap layer.

The concept of using a multilayer dielectric stack to obtain high reflectivities of electromagnetic waves by constructive interference can also be adopted to obtain dual wavelength or multi-wavelength mirrors with several Bragg mirror stop bands [9,45]. For a mirror with two target wavelengths \( \lambda_1 \) and \( \lambda_2 \) the thickness \( d_i \) of all dielectric layers has to be chosen to be \( d_i = \lambda_0/4n_i \) with \( \lambda_0 = 2\lambda_1\lambda_2/(\lambda_1 + \lambda_2) \). Furthermore, additional \( \lambda/4 \) layers have to be inserted at appropriate points in the Bragg mirror to shift the phase of the reflected light by 180°. The distance between these additional phase shifting layers should be \( \Delta\lambda = 2\lambda_1\lambda_2/(\lambda_1 - \lambda_2) \). These design rules result from the Bragg condition, which in the case of a conventional Bragg mirror states that maximum reflectivity will be obtained when the phase factor \(-\cos(2kd)\) becomes equal to unity. Similar to that, for a dual wavelength mirror the phase factor \(-[\cos(2k_1d) + \cos(2k_2d)]\) has to be maximized, which can also be written as \(-[2\cos(k_0d)\cos(2\Delta kd)]\), where \( k_0 = (k_1 + k_2)/2 \) is the averaged target photon wavenumber and \( \Delta k = (k_2 - k_1)/2 \) is the respective difference between the target wavenumbers. This phase factor term now can be viewed as the usual phase factor \(-\cos(2k_0d)\) modulated by a factor with the longer periodicity \( \Delta\lambda \), which is maintained in the dual Bragg mirror by the inserted phase shifting layers. An example of the calculated reflectivity spectrum of a dual wavelength Bragg mirror is shown in Fig. 4 for target wavelengths of 3 and 6 \( \mu \)m, and with refractive indices of \( n_1 = 5.5 \) and \( n_2 = 2.3 \) for the mirror layers, close to those observed for PbTe as material 1 and EuTe as material 2. To obtain two clear stop bands, five PbTe/EuTe

![Fig. 4. Reflectivity spectrum of a dual wavelength interference mirror with 5 layer pairs and additional phase shifting layers after each Bragg mirror pair. The calculation is done for \( n_1 = 5.5 \) and \( n_2 = 2.3 \) for target wavelengths of 3 and 6 \( \mu \)m.](Image)
Bragg mirror pairs were used with phase shifting EuTe layers after each Bragg mirror pair and an additional PbTe \( \lambda/4 \) layer on top of the structure. Mirrors with two stop bands can be used either for resonators for two-color light-emitting devices and detectors, or they can be used to obtain a single stop band with an increased width but with a reflectivity dip in its center by reducing the difference between the two target wavelengths \( \lambda_1 \) and \( \lambda_2 \).

In principle, the above concept can be extended to achieve mirrors with \( 2^n \) stop bands. The stop band width and the maximum reflectivity, however, decrease with increasing the number of target wavelengths. For the design of a four-wavelength mirror, a phase factor of the form \( \cos(2k_0d_0)\cos(2\Delta k_1 d_{\Delta k_1})\cos(2\Delta k_2 d_{\Delta k_2}) \) has to be considered [46]. Here, \( \Delta k_1 \) and \( \Delta k_2 \) are the spatial frequencies of the modulating terms and \( d_{\Delta k_1} \) and \( d_{\Delta k_2} \) are the corresponding layer thicknesses. The four target wavelengths with high reflectivity correspond to \( (k_0 + \Delta k_1 + \Delta k_2), (k_0 + \Delta k_1 - \Delta k_2), (k_0 - \Delta k_1 + \Delta k_2), \) and \( (k_0 - \Delta k_1 - \Delta k_2) \), where the parameters \( k_0 > \Delta k_1 > \Delta k_2 \) allow to choose three independent target wavelengths. The four-wavelength reflector requires additional quarter-wavelength layers, inserted into the initial Bragg mirror stack designed for the center wavelength \( \lambda_0 \), with periods of \( d_{\Delta k_1} \) and \( d_{\Delta k_2} \). For the GaAs/AlAs material system, the example of a four-wavelength mirror is shown in Ref. [30], where the insertion of the phase shifting layers was started at \( d_{\Delta k_1}/2 \) and \( d_{\Delta k_2}/2 \) from the top of the structure.

To obtain a large reflectance bandwidth for materials with small refractive index contrast, chirped structures were suggested [47–49], where the optical thicknesses of the respective layers were changed arithmetically. An increase of the band width by a factor of 2.7 was demonstrated [47] with this concept, for a 66-period AlAs/Al\(_{0.2}\)Ga\(_{0.8}\)As mirror with a target wavelength of \( \lambda_T = 880 \) nm. For this, the layer thicknesses of the high- and low-index materials were continuously varied between 0.75 and 1.25 times \( \lambda_T/4 \). Since the stop band of such a chirped Bragg mirror sequence exhibits several resonant reflection drops, additional layer pairs were inserted whose thicknesses were equal to one quarter of the wavelengths where the drops occur. Since chirping the layer thickness also results in a significant decrease of reflectivity, these kinds of mirrors are not suitable for laser resonators, but they can be applied to increase the efficiency of broad-band-emitting LEDs.

### 3. Material choice and MBE growth

There are several requirements for dielectric materials used for the epitaxial growth of Bragg mirrors. First, they have to be transparent at the target wavelength and they should exhibit a two-dimensional layer-by-layer growth on each other to obtain smooth heterointerfaces. It is advantageous to use materials with a high refractive index contrast in order to (a) limit the number of mirror pairs, (b) to obtain a large relative stop band width, and (c) to restrict light penetration into the mirrors. If the Bragg mirror layers are buried underneath a device, then the lattice constant as well as the thermal expansion coefficient should match that of the
substrate as well as that of the active layers. For some applications, also the electrical conductivity is a crucial parameter for the choice of the mirror material [50–52].

The refractive index at a wavelength of 1 \( \mu \text{m} \) of several binary compounds used for epitaxial Bragg mirrors is shown in Fig. 5 as a function of their lattice constant [53]. Due to the almost perfect lattice matching between Al and Ga based \( \text{A} \text{III} \text{B} \text{V} \) semiconductors like arsenides, antimonides and phosphides, and due to the fact that most electro-optical devices are based on these materials, also the majority of interference mirrors is fabricated from \( \text{A} \text{III} \text{B} \text{V} \) alloys. The reflectivity and stop band width of several III–V [45,50,51,54] mirrors with a target wavelength around 1.5 \( \mu \text{m} \) are shown schematically in Fig. 6. Due to the relatively small refractive index contrast around 15% for all III–V layer combinations a quite large number of Bragg mirror pairs (between 20 and 30) are necessary to obtain reflectivities in excess of 98%. This results in a total mirror thickness of several microns. By far a smaller number of Bragg mirror pairs are required when GaAs is combined with fluorides as low refractive index materials with refractive indices around 1.44. Shi et al. [55], e.g., demonstrated a reflectivity of more than 98% for only three layer pairs of GaAs/\( \text{BaF}_2 \), where 4 nm thick \( \text{CaF}_2 \) layers were inserted at each interface to reduce the lattice mismatch between these two materials.

In this work, we focus on dielectric mirrors fabricated from \( \text{Pb}_{1-x} \text{Eu}_x \text{Te} \) layers with Eu concentrations varying between 0 and 1. The lattice constant of this ternary compound varies between 6.46 and 6.6 \( \text{Å} \) [56] when \( x \) increases from 0 and 1, and the energy band gap \( E_g \) depends strongly on temperature as well as on Eu content with \( E_g = 190 \text{ meV} \) for \( x = 0 \) and 2.25 eV [57] for \( x = 1 \). Concomitant to \( E_g \), the refractive index \( n \) shows a large variation with \( x \), i.e., at a wavelength of 5 \( \mu \text{m} \) and room
temperature it decreases from 5.4 for $x = 0$ to 2.3 at $x = 1$ [58]. Furthermore, in lead salts the band extrema of the conduction band as well as of the valence band occur at the L-points of the Brillouin zone and the surfaces of constant energy are cigar-shaped ellipsoids with the main axis in [111] directions. Due to this many-valley band structure, the different effective masses of the longitudinal valley directing in growth direction and the three degenerate oblique valleys, enclosing an angle of 120° to each other, have to be taken into account to consider the optical properties of Pb$_{1-x}$Eu$_x$Te structures.

The samples were grown in a Riber 1000 MBE system onto BaF$_2$ (1 1 1) substrates using effusion cells for PbTe, Eu and Te$_2$. The Pb$_{1-x}$Eu$_x$Te ternary composition is determined by the PbTe to Eu beam flux ratio, and an excess Te$_2$ [59] flux was used to retain the correct stoichiometry. The growth rate, which was calibrated by a quartz crystal microbalance moved into the sample position, is typically around 2 μm/h for PbTe while it decreases with increasing Eu content to 0.77 μm/h for EuTe. From in situ reflection high-energy electron diffraction studies, the EuTe (1 1 1) surface shows a very strong tendency for (1 0 0) facetation due to the resulting lowering of the free surface energy and due to the lattice mismatch to the Pb$_{1-x}$Eu$_x$Te layers amounting up to 2%. As a result, 2D growth can be obtained only when the EuTe surface is kept close to the transition between the Eu- and Te-stabilized surface states, which can be easily distinguished because of their different surface reconstructions [60]. For the Te/Eu beam flux ratio of 2 that we used, this transition takes place at a substrate temperature of 260°C. Therefore, the EuTe layers were grown at substrate temperatures of 260± 10°C whereas for Pb$_{1-x}$Eu$_x$Te a growth temperature of 340°C was used.

Fig. 6. Schematic presentation of the maximum reflectivity and the spectral range of the mirror stop bands for Bragg mirrors made from different material combinations.
4. Experimental details

For the design of the Bragg mirrors, the knowledge of the refractive index as well as the extinction coefficient of the layer materials is required. These parameters can be deduced from fits of ellipsometry experiments or from reflectivity and transmission measurements, which we have performed by Fourier transform infrared (FTIR) spectroscopy of single reference layers for various temperatures and Eu concentrations. The transmission spectra were fitted using the transfer matrix method (Eqs. (2)–(6)) and a complex Kramers–Kronig conform model dielectric function $\varepsilon(E)$, which contains the nonparabolicity of the IV–VI band structure near the energy gap and the anisotropic many-valley band structure of the lead salts [61]. This dielectric function can be written as:

$$
\varepsilon(E) = \varepsilon_{\infty} - \frac{2B((E + i\Gamma_D)^2 - E_g^2)^{1/2}}{\pi (E + i\Gamma_D)} \arctanh \left( \frac{(E + i\Gamma_D)}{((E + i\Gamma_D)^2 - E_g^2)^{1/2}} \right).
$$

In this expression, $B$ is a dimensionless parameter that includes the oscillator strength of the fundamental transition, $i\Gamma_D$ is an imaginary damping parameter added to the photon energy $E$ to introduce level broadening, and $\varepsilon_{\infty}$ is the background dielectric constant. As demonstrated in Fig. 7 by the comparison of a measured and calculated transmission spectrum of a 3 μm thick PbTe layer at room temperature, the choice of the four parameters $E_g$, $B$, $\Gamma_D$, and $\varepsilon_{\infty}$ allows to reproduce the experimental data with high accuracy. From the energy dependence of the complex dielectric function, we obtain the dispersion of the refractive index shown in Fig. 8 for temperatures 77 and 300 K. It shows a maximum only at the energy band gap, which intensifies as the temperature decreases. With decreasing

![Fig. 7. Transmission spectrum of a 3 μm thick PbTe epilayer at room temperature. The experimental data (dots) can be well fitted by the use of the model dielectric function (Eq. 8) and the transfer matrix method.](image)
temperature the maximum shifts to lower energies due to decreasing energy band gap. Additionally, there is also a slight overall increase of the refractive index. For the Pb$_{1-x}$Eu$_x$Te ternary, with increasing Eu content x, the refractive index decreases dramatically, thus the refractive index contrast for the Bragg mirrors increases.

To characterize Bragg interference mirrors used for laser devices, reflectivities in excess of 99% have to be measured with high accuracy. This is difficult to achieve by just comparing the sample reflectivity with that of a broadband metallic reference mirror. Therefore, in this work we characterized the Bragg mirrors by transmission measurements and obtained the mirror reflectivity $R$ by $1 - T$, assuming negligible absorption in the layers. This is clearly fulfilled for undoped semiconductors below the fundamental absorption edge. Alternatively, a setup could be used, where the reflectivity of the reference mirror is eliminated by moving it between two positions (A and B shown in Fig. 9) to convert a “V” into a “W” configuration [62]. In these two configurations the optical paths are identical so that this technique allows to determine reflectivities with high accuracy. However, for this kind of measurement very homogeneous samples are required, since the reflectivity is probed at two distinct positions on the sample.

5. Mid-infrared lead salt Bragg mirrors

For the fabrication of lead salt Bragg mirrors we have utilized two different sample structures with different chemical compositions of the $\lambda/4$ layers. The corresponding parameters of two representative samples are shown in Table 1. For devices with good electrical characteristics, the Eu content should be restricted to values below 10%, in order to keep the lattice mismatch as low as possible and to
maintain a reasonable high carrier mobility, which is known to decrease strongly with increasing Eu content [63]. Sample S1 represents such a structure, consisting of 32 Pb$_{1-x}$Eu$_x$Te layer pairs with Eu contents of 1% and 6%. The 1% layer was grown as a PbTe/Pb$_{1-x}$Eu$_x$Te ($x = 6\%$) short-period superlattice digital alloy with a 4 nm superlattice period and a PbTe/Pb$_{1-x}$Eu$_x$Te thickness ratio of 5:1. Due to this digital alloy, the total number of layers is as large as 3230 for sample S1. The Bragg mirror was designed to match the band gap of PbTe at 77 K of 217 meV or a wavelength of 5.7 μm. To obtain maximum reflectivity for incidence of light from air the layer sequence starts with $x = 6\%$ on the BaF$_2$ substrate. Due to the long target wavelength and the large number of $\lambda/4$ layers required to obtain a high reflectivity, the total layer thickness of S1 amounts to 15.96 μm. For sample 2, $\lambda/4$ layers of Pb$_{0.93}$Eu$_{0.07}$Te and EuTe were used. This yields a much higher index contrast of 68% and therefore, high reflectivities can be achieved by a very small number of layer pairs. The total layer thickness of sample 2, a Bragg mirror with 3.5 periods of EuTe/

![Fig. 9. Sketch of the experimental “V–W” setup to measure reflectivity spectra independent of the reflectivity of the reference mirror.](image-url)

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Description</th>
<th>Target wavelength $\lambda_T$ (μm)</th>
<th>Number of $\lambda/4$ pairs</th>
<th>Layer sequence on BaF$_2$</th>
<th>$X_{\text{Eu}}$ (%)</th>
<th>Thickness (Å)</th>
<th>$\Delta n/n$ at $\lambda_T$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Bragg mirror</td>
<td>5.7 (77 K)</td>
<td>32</td>
<td>1. Pb$_{1-x}$Eu$_x$Te 5.5</td>
<td>2589</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. 50 period SL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(a) PbTe 0.9</td>
<td>2400</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) Pb$_{1-x}$Eu$_x$Te 5.5</td>
<td>40.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Bragg mirror</td>
<td>3.8</td>
<td>3.5</td>
<td>1. Pb$_{1-x}$Eu$_x$Te 7</td>
<td>2050</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. EuTe</td>
<td>4580</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1
Structural and optical parameters of the Bragg mirror samples S1 and S2. Layer thicknesses and compositions were determined by X-ray diffraction. The optical data are obtained from transmission measurements.
Pb$_{0.93}$Eu$_{0.07}$Te layer pairs and a target wavelength of 3.8 μm, amounts to only 2.55 μm.

For structural characterization X-ray diffraction spectra of the samples were measured using a high resolution X-ray diffraction set-up with a Bartels primary monochromator and Cu K$_{\alpha 1}$ radiation. The $\Omega/2\theta$ diffraction spectra recorded around the Bragg 222 reflection are shown in Fig. 10. For sample 1 the main characteristics of the diffraction spectrum in Fig. 10(a) are two main peaks from the Pb$_{1-\lambda}$Eu$_{\lambda}$Te layers of the $\lambda/4$ pair with a different Eu content. The peak splitting of only 257 arcsec indicates a different lattice constant of about 0.25%. In addition, widely spaced satellite peaks from the 1% Pb$_{1-\lambda}$Eu$_{\lambda}$Te digital alloy superlattice are observed, but no satellite peaks from the periodic $\lambda/4$ pair stacking are resolved due to the very large Bragg mirror periods of about 0.5 μm. From the superlattice period of the pseudoalloy layer, the growth rates and $\lambda/4$ layer thicknesses can be deduced. The full width at half maximum (FWHM) of the diffraction peaks is about 99 arcsec.

For S2 (Fig. 10(b)), the splitting between the EuTe and the Pb$_{1-\lambda}$Eu$_{\lambda}$Te SL0 peaks of 1998 arcsec is about ten times larger than that for sample S1. The lattice constants derived from the peak positions indicate that each $\lambda/4$ layer has almost relaxed to its bulk lattice constant in spite of the 2% lattice mismatch between the layers. This is
due to the fact that the thicknesses of the $\lambda/4$ layers by far exceed the critical thickness for strain relaxation. As a result, a high density of misfit dislocations is formed at each of the heterointerfaces, resulting also in a threefold broadening of the X-ray diffraction peaks to a FWHM of 300 arcsec. However, as shown below, this does not degrade the very high optical quality of the mirror structure.

The high lateral and vertical homogeneity of our mirror structures are demonstrated by the cross-sectional scanning electron micrograph (SEM) of a Pb$_{0.94}$Eu$_{0.06}$Te/Pb$_{0.99}$Eu$_{0.01}$Te layer stack in Fig. 11. This reference sample was first mesa etched with a Br/HBr/H$_2$O solution and subsequently selectively etched using a CH$_4$/H$_2$ plasma in a barrel reactor. With this method, the layers with lower Eu content are etched deeper [64], and hence appear darker in the SEM image than those with higher Eu content. The left edge in the picture is the side wall of the mesa stripe which is wedge shaped due to the wet chemical etching process with the Br solution.
The FTIR transmission spectrum of sample S1 at 77 K is shown in Fig. 12. This mirror exhibits a pronounced stop band region centered at an energy of 1760 cm$^{-1}$ and exhibits a width of 80 cm$^{-1}$. As shown in detail in the inset of Fig. 12, a minimum transmission of about 0.3% is observed at the center of the stop band, corresponding to a reflectivity exceeding 99%. Such high reflectivities are well suited for VCSEL devices. The spacing of the Fabry–Perot fringes is very narrow due to the large total thickness of the 32-period sample. The transmission cut-off at 2200 cm$^{-1}$ corresponds to the fundamental absorption of the Pb$_{1-x}$Eu$_x$Te layers with $x = 1\%$. The numerical calculation (solid line) is in very good agreement with the experimental data, apart from the slight deviation near the absorption edge region. This deviation at higher energies is indicative of a small inhomogeneity of the layer thickness (below 1%) in the measured area of the sample.

Due to the dependence of the refractive index on temperature, the Bragg mirror characteristics such as stop band reflectivity, resonance wavelength and stop band width also depend on the sample temperature. Therefore, we have examined the optical characteristics of the 32-period high reflectivity mirror S1 as a function of temperature. The results are depicted in Fig. 13. Part (a) shows the stop band limits for temperatures from 10 K to 300 K. Within these limits, the transmission of the mirror is below 0.5%. With increasing temperature, the stop band center (resonance energy) shifts to higher energies from 1750 cm$^{-1}$ at 10 K to 1845 cm$^{-1}$ at 300 K, and the stop band width decreases from 90 cm$^{-1}$ at 10 K to 40 cm$^{-1}$ at 300 K. The comparison of the temperature dependence of the mirror stop band and of the energy band gap of PbTe [58] is shown in Fig. 13(b). It is clearly seen that a matching of the PbTe band gap emission to the mirror stop band is only given in a small
temperature range between 70 and 100 K. This is due to the rapid increase of the PbTe band gap energy with temperature, which is typical for lead salt compounds.

Although the reflectivity of S1 in the stop band is sufficient for laser resonators, for probing the temperature behavior of lead salt devices, a much wider Bragg mirror stop band is desired. This can be achieved by using a larger refractive index contrast as in the case of sample S2. The room temperature transmission spectrum of S2 in Fig. 14 clearly shows the mirror stop band around the target energy of 2600 cm\(^{-1}\) (3.8 \(\mu\)m). The spacing of the Fabry–Perot interference fringes is much larger than in the case of S1, due to the reduced total thickness of the Bragg mirror stack. The transmission minimum within the stop band, shown in the inset of Fig. 14 on an enlarged scale, is as small as that for S1, in spite of the small number of Bragg layer pairs of 3. In contrast, the width of the stop band of about 1300 cm\(^{-1}\), is 16 times larger than that of S1. In particular, the stop band width is larger than the total band gap energy shift of PbTe and PbSe between room temperature and 0 K.

For a comparison with results obtained from other material combinations it is useful to relate the stop band width \(\Delta \lambda\) to the center wavelength \(\lambda_\text{T}\). For sample S2 this relative stop band width \(\Delta \lambda/\lambda_\text{T}\) gives a value of 50%. An even wider stop band width of 59% was demonstrated only for a mirror with PbTe and EuTe \(\lambda/4\) layers. This value represents, to the best of our knowledge, the highest relative stop band width obtained for MBE grown Bragg reflectors. As shown in Fig. 15, it is much higher than the relative width typically obtained by the use of combinations of III–V
and II–VI [6,66] semiconductors used in the visible spectral range and a wavelength of 1.5 μm. The stopband width is also larger than that of Bragg mirrors using combinations of wide band gap fluorides as low refractive index materials with GaAs [55,67] or Pb$_{1-x}$Sr$_x$Se [68] as high index materials (see Fig. 15).

![Fig. 14. Room temperature transmission spectrum of a three-period Pb$_{0.93}$Eu$_{0.07}$Te/EuTe Bragg mirror (S2). The inset shows the region of the mirror stop band whose target energy coincides with the energy band gap of PbTe at room temperature. The solid line is the calculated transmission spectrum and the dots are the experimental results.](image)

![Fig. 15. Relative stop band widths for various Bragg mirrors with different target wavelengths in the visible and mid-infrared spectral range, fabricated from different material systems. The data are taken from Refs. [6,45,50–52,54,55,65–68].](image)
6. Applications

Due to the large variety of reflectivities accessible by dielectric mirror stacks, there are many applications for epitaxial Bragg mirrors that can be integrated within opto-electronic devices. In most applications, epitaxial Bragg mirrors are combined with a second mirror to form a planar Fabry–Perot resonator (FPR). FPRs can be used either for light amplification [69–71], to control the spectral and spatial distribution of spontaneous emission generated in an active layer within the resonator [72], or even to manipulate the spontaneous emission rate [73]. These effects have been used to obtain stimulated emission in VCSELs [2,3,74], to increase the efficiency of RCLEDs [5,75,76], and to obtain high contrasts in Fabry–Perot reflection modulators [12–14]. When the distance between the two mirrors of the FPR is decreased to dimensions comparable to the optical wavelength in the medium, quantum mechanical effects like the formation of cavity polaritons can be observed [18,77–79]. While FPRs for the visible and near infrared spectral range using epitaxial Bragg mirrors with good optical quality have been fabricated already since 1975 [80], FPRs for the mid-infrared were presented only very recently [81–83]. In the following, several applications of novel lead salt FPRs with resonance wavelengths between 3 and 6 μm are discussed.

6.1. Ultra-high-finesse lead salt microcavities

Mid-infrared microcavities with an ultra-high-finesse can be fabricated using PbTe and EuTe as material combination for the Bragg mirrors, and PbTe as cavity material. This is exemplified by cavity sample C1, consisting of four PbTe (3210 Å)/EuTe (7764 Å) Bragg mirror pairs at the bottom and three mirror pairs at the top of the sample, with a half wavelength PbTe cavity (6420 Å) in between. The FTIR transmission spectrum at room temperature of this microcavity is shown in Fig.16. Similar to the case of the Bragg mirrors discussed above, it features a very wide mirror stop band as well as Fabry–Perot interference fringes outside this region, with a cut-off of the transmission at 2600 cm$^{-1}$ due to the absorption edge of PbTe. The main feature of interest here is the very narrow single cavity resonance maximum at 1370 cm$^{-1}$ ($\lambda = 7.3 \mu$m) in the center of the stop band, with a full width at half maximum (FWHM) of only 1.8 cm$^{-1}$ (225 μeV). This narrow resonance provides evidence for the high quality of our half-wavelength microcavity. The solid line represents the calculated theoretical transmission spectrum which is in excellent agreement with the experimental data.

The cavity resonance peak of the second microcavity sample C2, a $\lambda/2$ PbTe microcavity with five PbTe/EuTe quarter wavelength layer pairs (with layer thicknesses of 2365 and 5574 Å, respectively) as top and bottom mirror, is depicted in Fig.17. The Lorentzian-shaped sharp resonance located at $v_r = 1877$ cm$^{-1}$ ($\lambda_r = 5.32 \mu$m) exhibits a FWHM of only 0.63 cm$^{-1}$ (78 μeV). This value corresponds to a cavity quality factor or finesse $F = \lambda_r/\Delta\lambda_r = v_r/\Delta v_r$ of 2980 assuming an $m = 1$
Fig. 16. Transmission spectrum at 300 K of a ($\lambda/2$) PbTe/EuTe microcavity with a four-pair bottom Bragg mirror and a three-pair top mirror (sample C1). The experimental data (dots) are in good agreement with the theoretical transmission spectrum (solid line).

Fig. 17. Cavity resonance peak of a ($\lambda/2$) PbTe/EuTe microcavity with a five-pair top and bottom Bragg mirror (sample C2). The resonance width of 78 µeV corresponds to an ultra-high effective finesse of 1700. The inset shows a SEM of the selectively etched cleavage edge of the microcavity structure with an additional $\lambda/4$ EuTe layer on top.

order of the cavity. The order $m$ of the cavity is given by the optical thickness of the cavity $(n \cdot d)$ as [84]

$$m = \frac{nd}{\lambda_c/2}$$  \hspace{1cm} (9)
For dielectric mirrors, the light penetrates to some extent into these mirrors. This effect has to be taken into account by introducing an effective optical cavity length \( l_{\text{eff}} \), which can be derived from the refractive indices of the mirror layers at the resonance energy [84]:

\[
\begin{align*}
    l_{\text{eff}} &= \left( m + \frac{n_1}{n_2 - n_1} \right) \frac{\lambda_r}{2},
\end{align*}
\]

where \( n_1 \) and \( n_2 \) are the refractive indices of the low and high index layer materials, respectively. With \( n_{\text{PbTe}} = 5.39 \) and \( n_{\text{EuTe}} = 2.3 \), the effective order \( m_{\text{eff}} \) of our cavity is 1.74, and hence the effective cavity finesse \( F_{\text{eff}} = F/m_{\text{eff}} \) is 1700. This represents, to the best of our knowledge, by far the highest finesse for mid-infrared Fabry–Perot cavities reported so far, and even exceeds the ultra-high effective finesse value of 1470 obtained for an optimized GaAs/AlAs microcavity for \( \lambda = 930 \text{ nm} \) [84]. In comparison, a finesse of 350 was reported for a mid-infrared CdHgTe microcavity at 3 \( \mu \text{m} \) [85], which was derived from the expected mirror reflectivities. Other high finesse values of 650 at about 490 nm for ZnCdSe [86] and of 1000 at 1.5 \( \mu \text{m} \) for AlGaSb [87] were calculated just by using the \( F = \lambda_r/\Delta \lambda_r \) expression without taking into account the actual effective cavity lengths and the order of the cavities (8 and 2, respectively). Therefore, the effective finesse in both cases is actually at least a factor of three lower than the quoted values. The inset in Fig. 17 shows an SEM image of the cleavage edge of the microcavity sample with the five Bragg pair mirrors and an additional \( \lambda/4 \) EuTe layer on top. It evidences the good quality of the MBE growth in revealing high lateral and vertical homogeneity and small interface roughness of cavity sample C2.

Apart from the high quality MBE growth of the cavity samples, the very high finesse of the lead salt microcavities C1 and C2 is based on the high refractive index contrast between EuTe and PbTe. This high contrast results not only in high reflectivities of the Bragg mirrors and a large stop band width, but it also limits the penetration of light into the dielectric mirrors. The penetration length is about one seventh of that obtained by the use of other semiconductor combinations, so that by PbTe/EuTe stacks actual half wavelength cavities can be achieved.

### 6.2. Mid-infrared vertical-cavity surface-emitting lasers

For laser spectroscopy in the mid-infrared until now predominantly diode lasers fabricated from IV–VI semiconductors have been used [31,88]. In comparison to other mid-infrared lasers, the advantages of lead salt lasers are the large wavelength tunability of more than 2 \( \mu \text{m} \) [89] and the narrow line widths in the order of \( 10^{-4} \text{ cm}^{-1} \) [30]. Furthermore, at wavelengths longer than 3 \( \mu \text{m} \) lead salt laser diodes exhibit higher operation temperatures in CW than laser diodes from II–VI and III–V materials [25]. The fact that by far higher operation temperatures are reached in pulsed mode [24] indicate that improving the head dissipation could allow to increase the maximum operation temperature substantially. Therefore, we have fabricated IV–VI semiconductor laser devices on BaF\(_2\) substrates which exhibit a 5 times larger thermal conductivity than the lead salt substrates used for the IV–VI lasers until
now. For BaF$_2$, cleaving results in [111] oriented facets, so that no lateral laser resonators can be formed. This makes it necessary to grow vertical resonators with epitaxial Bragg mirrors to achieve lead salt mid-infrared lasers for improved heat dissipation. The planar integration and surface-emission of VCSELS provide further major advantages over edge-emitting lasers such as circular beams, low divergence, single-mode operation and simplified fabrication of high power laser arrays.

Similar to the microcavity samples C1 and C2, the laser sample C3 consists of two high reflectivity EuTe/Pb$_{1-x}$Eu$_x$Te Bragg mirrors with three $\lambda/4$ layer pairs and a two-wavelength Pb$_{1-x}$Eu$_x$Te microcavity ($x_{Eu} = 5\%$) in between. As an active material, four PbTe quantum wells (QW) of 20 nm thickness were inserted in the cavity at the antinode positions of the electric field. The Eu content of 5% in the ternary layers yields a refractive index contrast of 80% with respect to EuTe and therefore, a stop band reflectivity above 99.5%. On the other hand, due to the strong increase of the energy band gap of Pb$_{1-x}$Eu$_x$Te with increasing Eu content [58], 5% Eu already yields a quantum confinement of 150 meV within the PbTe QWs. Thus the Bragg mirror layers are fully transparent for the QW emission. Due to the very strong temperature dependence of the energy band gap of the lead salt compounds, the microcavity structure must be tailored for a certain operation temperature, which was chosen as 77 K in this case, with a corresponding PbTe QW emission around 5 $\mu$m. Thus the $\lambda/4$ layer thicknesses in the three-period Bragg mirrors were 599 nm for EuTe and 272 nm for Pb$_{0.95}$Eu$_{0.05}$Te, and the cavity length was 2170 nm.

The cross-sectional scanning electron microscopy image of the complete VCSEL structure is shown in Fig. 18(a). In SEM, the four PbTe quantum wells within the cavity region can be clearly distinguished. The high optical quality of the microcavity structure is demonstrated by the FTIR transmission spectrum depicted in Fig. 18(b). Within the wide stop band region, three sharp cavity resonance peaks at 179, 221, and 264 meV are observed, corresponding to the cavity modes of the order $m = 3$, 4, and 5. The full width at half maximum of the peaks is 0.2–0.5 meV, which indicates a cavity finesse as high as 800 at 300 K. Optical pumping of the VCSELS was performed at 1064 nm with a pulsed Nd:YVO$_4$ laser normally incident to the surface with a pulse length of 10 ns at a repetition rate of 100 Hz. The stimulated VCSEL emission spectrum at 70 K is shown in Fig. 19(a), together with the 70 K transmission spectrum in the same spectral region. Clearly, the laser emission at 257 meV (4.82 $\mu$m) coincides with the 5th order cavity mode. The FWHM of the emission is only 0.4 meV, which is essentially determined by the limited resolution of the spectrometer set-up. The narrow line width is not only much smaller than the photoluminescence of the usual PbTe/Pb$_{1-x}$Eu$_x$Te quantum wells (typically 4 meV [90]), but also smaller than the width of the cavity mode. This spectral narrowing is an indication for stimulated emission. The angular dependence of the emission shows a rapid drop in intensity even for slight deviations of the emission angle off the surface normal direction. Such a narrow forward directed output is characteristic of a planar microcavity [91].

The dependence of the integrated output intensity on the pump power density is shown in Fig. 19. It exhibits the typical linear behavior of optically pumped semiconductor lasers for pump powers above a threshold of $P_{th} = 1050$ kW/cm$^2$. 
with a narrowing of the line width with increasing power (see insert in Fig. 19(b)).
Below threshold no signal was found due to insufficient detector sensitivity. Because
the energy band gap of the 5% Pb$_{1-x}$Eu$_{x}$Te  4 layers is only 500 meV, the 1064 nm
pump laser is strongly absorbed by the top mirror, with an estimated absorption
coefficient of 5 x 10$^{-4}$ cm$^{-1}$. As a consequence, less than 5 x 10$^{-3}$ of the incident light
is actually coupled into the cavity region, i.e., the effective threshold power density is
of the order of 5 kW/cm$^2$.

Further evidence for microcavity lasing arises from temperature-dependent
emission measurements [92]. Whereas at low temperatures around 4 K, emission is
observed at the $m = 4$ cavity mode at 5.87 μm (see inset of Fig. 20(a)), at 35 K the
emission switches to the $m = 5$ resonance at 4.82 μm. As shown in Fig. 20(a), when
the temperature is further increased, the output power strongly increases with little
change in the emission wavelength (see □ Fig. 20(b)). At 70 K, the emission intensity
reaches a maximum, but rapidly decreases for temperatures higher than 80 K and
vanishes completely above 85 K.

To explain this behavior, the temperature dependence of the intrinsic QW
emission in relation to the cavity modes has to be considered. Whereas from
temperature-dependent FTIR measurements the positions of the cavity modes are
almost constant in temperature (● in Fig. 20(b)), the interband transition energies
within the quantum wells rapidly increase as the temperature increases due to the
increase of the PbTe energy band gap. As a consequence, a coincidence of electronic
interband QW transitions and the cavity resonances can exist only for a certain
temperature range. This is shown in Fig. 20(b), where the interband transition
energies within the 20nm PbTe quantum wells obtained from envelope function
calculations [93] and the measured cavity mode positions are plotted as a function of
temperature. At very low temperatures an overlap exists between the
$m = 4$ mode and the 2D joint density of states of the ground states of the longitudinal energy
valleys along [1 1 1] growth direction in the conduction and valence bands (both
labeled $1I$) and therefore, emission is due to $(1–1)I$ transitions. As the temperature is
raised, the transition energy of the valleys oblique to the growth direction (labeled
$(1–1)$) moves closer to the $m = 5$ cavity mode and the laser emission switches to the
higher cavity mode. This is due to the fact that the joint density of states of the threecold degenerate oblique valleys is about a factor of 10 larger than that of the
longitudinal valley. The mode hopping and the fact that only one emission line is
observed at each temperature is another confirmation for the stimulated type of
emission from the cavity structure.

From the calculations, the $(1–1)^{\circ}$ transition moves to energies higher than the
$m = 5$ cavity mode when the temperature is above 85 K. This is exactly the
temperature where the laser action stops in the experiments. Moreover, the temperature where the maximum output intensity occurs agrees quite well with the situation where the bottom of the $(1-1)^o$ joint density of states is just below the cavity mode. This behavior is a clear indication that the maximum operation temperature of our VCSEL is not due to intrinsic effects but is only determined by the particular cavity design. Therefore, much higher operation temperatures are expected for cavity structures with mode positions matching the QW emission at higher temperatures.

In order to obtain laser operation from a lead salt VCSEL at room temperature we changed the sample design in several respects [94]. The cavity modes were shifted to shorter wavelengths around $3\mu m$ to match the band gap of PbTe at room temperature. To make the top mirror transparent at the wavelength of optical excitation, the Eu content in the ternary layers of the top mirror was increased to 20%. In addition, for optical pumping a longer wavelength of $1.97\mu m$ was used. To achieve a higher gain, the number of PbTe quantum wells was increased to nine. To assure that sufficiently high carrier densities are obtained, optical pumping was performed by pulses with 100 fs duration.

![Fig. 20. (a) VCSEL emission spectra measured at different temperatures for a constant pump power of $2.8P_{th}$. (b) Measured cavity resonance positions (solid lines) within the 20nm PbTe quantum wells plotted versus temperature. The open squares indicate the observed photon energies of the VCSEL emission.](image)
Two microcavity samples were investigated with different target wavelengths of the central cavity mode of $\lambda = 3.1\,\mu m$ for sample C4 and of $\lambda = 3.6\,\mu m$ for sample C5. This was achieved by an adjustment of the thickness of the cavity and the Bragg mirror layers. The cross-sectional SEM of one of these samples is depicted in Fig. 21(a) together with a sketch of the active cavity region showing the position of the nine 20 nm wide PbTe QWs inserted in the cavity close to the five antinode positions of the electric field. The room temperature reflectivity spectrum of sample C4 is depicted in Fig. 21(b). It shows the wide Bragg mirror stop band from 2400 to 3950 cm$^{-1}$ with high reflectivity with three microcavity resonance dips of the order $m = 3, 4$ and 5. The strong and narrow resonance $m = 3$ at 2581 cm$^{-1}$ exhibits a relatively high finesse of 150, whereas the higher $m = 4$ and 5 modes are less pronounced and broader indicating a strong damping. This damping is due to absorption in the nine 20 nm PbTe QWs with an effective band gap of 2600 cm$^{-1}$ (3.8 $\mu m$). It is strongest in the center of the Bragg mirror stop band which coincides with the $m = 4$ mode at 3111 cm$^{-1}$, exhibiting a line width of 70 cm$^{-1}$. Above 4000 cm$^{-1}$ and below 2500 cm$^{-1}$ again Fabry–Perot interference fringes are observed. The spectrum of the pump laser pulse that peaked at 5060 cm$^{-1}$ with a width of 200 cm$^{-1}$ is shown by the dashed line in Fig. 21(b). The peak position is higher than the absorption edge of the barrier layer in the active region at 3900 cm$^{-1}$, but it is considerably smaller than the absorption edge of the top mirror at 6300 cm$^{-1}$.

![Fig. 21. (a) Cross-sectional SEM of sample C4 together with a sketch of the cavity region. The chemical contrast between distinct layers is visualized by selective etching. The dotted line represents the standing electromagnetic wave in the cavity. (b) Reflectivity spectrum of sample C4 compared with that of the pump pulses. The arrow indicates the absorption edge of the 20 nm wide PbTe quantum wells.](image-url)
Thus, optical pumping results in the creation of electron-hole-pairs only within the cavity-active region (inserted PbTe QWs) and not within the top mirror. With the energy of the pump laser, the sample exhibits a reflectivity of about 50%. Sample C5 shows a similar reflectivity spectrum as sample C4, except that the Bragg mirror stop band as well as the cavity resonances are shifted to lower energies by about 400 cm\(^{-1}\) so that the central mode of C5 is tuned to 2830 cm\(^{-1}\).

For laser excitation, we used 100 fs long pulses at a wavelength of 1.97 \(\mu\)m with a repetition rate of 1 kHz, generated in an optical parametric amplifier, which is pumped by intense 800 nm pulses from a Ti:sapphire regenerative amplifier [95,96]. The excitation laser beam was directed on the sample at an angle of 15° and focused down to a spot diameter of 400 \(\mu\)m. Room temperature emission spectra of sample C4 for various pump energy densities are shown in Fig. 22(a). For an excitation energy density of 0.8 mJ/cm\(^2\), the emissionspectrum shows a Lorentzian-shaped line centered at 3200 cm\(^{-1}\) with a width of 160 cm\(^{-1}\). Increasing the excitation density to 1 mJ/cm\(^2\) results in a considerable narrowing of the emission spectrum and a drastic rise of the luminescence intensity. Both effects indicate the onset of stimulated emission. For excitation powers above 1 mJ/cm\(^2\), the line width becomes larger again and the integrated emission intensity of the sample linearly increases with increasing pump power. Such a linear dependence is expected for laser emission, and it is shown in detail in Fig. 22(b) giving a laser threshold energy density of 0.83 mJ/cm\(^2\) for sample C4 at room temperature.

In contrast to the 77 K VCSEL described above, the emission spectra in Fig. 22(a) are about 100 cm\(^{-1}\) blue shifted with respect to the central cavity resonance as determined by the FTIR measurements. Furthermore, the width of the emission spectrum is narrower than that of the 77 K VCSEL.
spectra is considerably larger than that of the cavity resonance peak in the reflectivity experiments. Both effects are due to the excitation with high intensity fs pulses. Taking into account that the carrier lifetime in PbTe is larger than the excitation pulse duration [22], the carrier concentration in the microcavity layer can be estimated for the pump energy densities used. It exceeds $1 \times 10^{19} \text{ cm}^{-3}$ immediately after the excitation pulse and subsequently decreases due to photon emission and nonradiative recombination. This dynamic band filling modulates the effective band gap and concomitantly the refractive index, which thus modulates even the cavity resonance position. This clearly leads to a broadening of the time-averaged emission spectra from the sample. The observed $100 \text{ cm}^{-1}$ blue shift of the emission spectra corresponds to a reduction of the refractive index of $3\%$, a value that has been already observed in PbTe epilayers under ps excitation giving carrier concentrations of $10^{17} \text{ cm}^{-2}$ [23].

As shown in Fig. 22(b), at room temperature sample C5 exhibits superior laser characteristics than sample C4, with a lower laser threshold of only $0.32 \text{ mJ/cm}^2$ and a much steeper slope of the linearly increasing integrated output intensity with increasing pump energy. In spite of the fact that for pump energy densities exceeding $2 \text{ mJ/cm}^2$ the output intensity starts to level off due to saturation effects (see inset in Fig. 22(b)), C5 yields a more than three times larger output intensity than C4, even up to the highest pump pulse energy of $19 \text{ mJ/cm}^2$. This superior laser performance of C5 is a result of the lower density of states and of the higher population density after carrier thermalization at the energy of the microcavity resonance, which is just about $100 \text{ cm}^{-1}$ above the band edge of the PbTe quantum wells.

The dependence of the emission spectra of both samples on operation temperature is demonstrated in Fig. 23. For sample C5 and for an excitation energy density of

![Fig. 23. Emissionspectrafor varioustemperatures showingthelaseroperationofsamples C5 (a) and C4 (b) up to 65°C. The inset shows the peak transmission (circle symbols) and the full width at half maximum (FWHM—square symbols) of the $m = 4$ mode of sample C5, determined from transmission measurements.](image)
4 mJ/cm$^2$ (Fig. 23(a)), the stimulated emission at 2850 cm$^{-1}$ strongly decreases when the sample temperature is increased from room temperature to 30°C, and it completely quenches at 35°C. This quenching is only partially due to an increase of nonradiative recombination but rather by the 70 cm$^{-1}$ blue shift of the band edge of the PbTe quantum well when the temperature is increased by 20°C. Thus, the QW gain spectrum shifts out of the cavity resonance mode and the laser operation is quenched. This interpretation is confirmed by the results from temperature-dependent CW FTIR experiments summarized in the inset of Fig. 23(a), where a step-like increase of the cavity resonance transmission as well as a decrease in the resonance line width is observed when the temperature rises above 35°C. Thus, both observations indicate a step-like decrease of the optical absorption coefficient at the temperature where the laser operation is quenched. For sample C4 this intrinsic process is not expected to limit the maximum operation temperature to less than 150°C, because for C4 the energy of the central cavity mode is 400 cm$^{-1}$ higher than for sample C5. The emission spectra of sample C4 excited with an energy density of 8 mJ/cm$^2$ are shown in Fig. 23(b). With increasing sample temperature the laser output intensity at first decreases only slowly. Above 55°C the intensity decreases rapidly and completely quenches at 70°C. As shown in Fig. 23(b), the laser threshold for C4 increases slightly with increasing temperature from 0.83 mJ/cm$^2$ at room temperature to 1 mJ/cm$^2$ at 50°C. In contrast to C5, this temperature dependence is influenced only marginally by the shift of the QW gain spectrum. Indeed, within this temperature range between 20 and 70°C CW FTIR experiments do not indicate any significant change of the absorption coefficient at the cavity resonance energy. Therefore, it can be concluded that the observed quenching of the laser emission at 70°C is dominated by nonradiative processes like Auger recombination and multiphonon emission.

6.3. Spectroscopy on correlated self-organized quantum dots in a vertical resonator

In Fabry–Perot resonators, the incident light passes the cavity region between the two mirrors several times, leading to a strong intensity enhancement inside the cavity. This can be used not only to obtain laser oscillations in optical active media but also to increase the absorption of layers with small optical density. The latter is usually used to achieve high contrast ratios in Fabry–Perot reflection modulators [12,13]. In this section, we demonstrate the use of a vertical cavity for investigation of the weak absorption of a superlattice of self-assembled PbSe Stranski-Krastanow islands embedded in lattice mismatched Pb$_{0.95}$Eu$_{0.05}$Te barriers [97]. In these quantum dot superlattices, the elastic interactions between the growing dots on the surface and those buried within the previous ones lead to a unique FCC-like ABCABC… vertical dot stacking sequence and a nearly perfect lateral ordering within the growth plane, corresponding to the formation of self-organized trigonal 3D lattices of dots [97,98].

While the ordering mechanism and the topography of the correlated PbSe quantum dot superlattices have been clarified [97–101], absorption measurements did not give conclusive results on the optical and electronic properties of the quantum
dots, due to the small optical density of the dots, and due to the fact that absorption spectra of lead salt films are dominated by strong Fabry–Perot interference fringes due to the refractive index contrast between the layer and the BaF$_2$ substrate. To overcome these problems, we have embedded a 140-period superlattice of 5-monolayer PbSe dots alternating with 48 nm Pb$_{0.95}$Eu$_{0.05}$Te spacer on a 3 μm Pb$_{0.95}$Eu$_{0.05}$Te buffer between two Bragg mirrors, forming a vertical cavity. Due to the large cavity length of 10.3 μm, within the stop band region of the Bragg mirrors 16 cavity resonances are supported with an energy distance of only 88 cm$^{-1}$. The FTIR transmission spectrum of the cavity stop band region is shown in the inset of Fig. 24. At 300 K the absorption edge of the quantum dots is well above the cavity stop band. Thus, the whole structure represents an unfilled optical cavity, which is also evident from the mirror symmetric distribution of the resonance peak heights. As the temperature is lowered, the dot absorption shifts into stop band region due to decreasing PbSe band gap. As a result, the higher energy cavity modes become strongly damped leading to a decrease in their amplitude and a broadening of their width. From the ratio between the width and the amplitude ($W/H$) of the damped modes, the quantum dot absorption can be directly measured. As shown in Fig. 22, at a temperature of 50 K $W/H$ gives small values up to an energy of 2400 cm$^{-1}$ (4.2 μm) above which $W/H$ strongly increases. In addition to the strong increase of $W/H$ as a function of energy, a shoulder is clearly observed at 2600 cm$^{-1}$. A comparison to model calculations indicates that this shoulder is caused by absorption from the oblique valleys of the PbSe quantum dots. Hence, the strong
absorption above the shoulder denotes absorption from wetting layers, whereas the small increase of $W/H$ at 1800 cm$^{-1}$ indicates the longitudinal valley.

7. Summary

The design and fabrication of Bragg mirrors consisting of stacks of dielectric $\lambda/4$ layers with one or several reflectivity stop bands was described. To obtain high reflectivities with a limited number of Bragg mirror pairs either material combinations with a large refractive index contrast or hybrid structures of dielectric and metallic mirrors can be used. A large width of the mirror stop band is obtained by using materials with a large refractive index contrast or by mirrors with several target wavelengths. Alternatively, chirped Bragg mirror structures can be applied to achieve relatively large stop band width. Epitaxially grown Bragg mirrors from lead salt compounds are demonstrated with reflectivity stop bands in the mid-infrared spectral range. Due to the strong temperature dependence of the lead salt energy band gap, mirrors with large stop bands are very advantageous for electro-optical devices fabricated from these materials. This can be achieved, e.g., by combinations of lead salts with refractive indices up to 5.9 with the large band gap semiconductor EuTe as low refractive index dielectric material. Such Bragg mirrors exhibit relative stop band widths of up to 60%, several times larger than those typically obtained in the visible or near-infrared spectral range. In addition, these mirrors offer the possibility to obtain reflectivities above 99% with just three Bragg mirror pairs. Based on such high reflectivity Bragg mirrors, we have demonstrated planar microcavities with an ultra-high effective finesse giving values up to 1700. Vertical-cavity surface-emitting lasers for the mid-infrared are obtained by introducing PbTe quantum wells with PbEuTe barriers as optically active medium between the dielectric Bragg mirrors. At wavelengths between 3 and 6 $\mu$m, stimulated emission is achieved by optically pumping with pulsed laser sources. Due to the different temperature dependences of the resonator modes and of the band gap energy, for each operation temperature a different design of the vertical resonator is required. Laser operation is demonstrated up to 65°C. Above this temperature nonradiative recombination processes become dominant. Finally, we have shown the ability to use vertical resonators to study the absorption of materials with a small optical density. In the example presented, the enhanced light absorption in the cavity is used to detect the band gap of a superlattice containing self-organized PbSe quantum dots, which are highly ordered in vertical and lateral direction.

References