

Chapter 2

VCSEL Fundamentals

The fundamentals of semiconductor lasers in general and vertical-cavity surface-emitting lasers (VCSELs) in particular are explained in this chapter. Basic design principles that are especially important for VCSELs and that enabled the development of present high-speed VCSELs, such as distributed Bragg reflectors and oxide-apertures are explained in detail with many examples. A broad range of different VCSEL applications exist, resulting in many different VCSEL designs and the use of different material systems to build the VCSELs. The intention of this chapter is not to provide a complete introduction of VCSELs for all possible emission wavelengths or applications, but rather to present those design principles that directly apply to the GaAs-based VCSELs presented in this dissertation for optical data transmission with peak emission wavelengths in the range of approximately 850–1060-nm.

2.1 Laser Principle

The well-known acronym “laser” stands for “**L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation”. Albert Einstein first postulated *stimulated emission* of radiation in 1916 [1]. A vast number of different lasers exist that all differ in the design and properties, but that are all based on the same principles: creation and amplification of light via stimulated emission in a cavity. In the following these basic laser principles that apply for all different lasers are explained.

2.1.1 Creation of Light

In a radiative equilibrium of a quantum mechanical system, for example a single atom, three types of photon electron interaction exist. First an excited electron with the Energy E_1 can spontaneously relax to a lower energy level E_2 under emission of a photon with the energy $E_{21} = E_1 - E_2 = h\nu$, where h is the Planck constant and ν

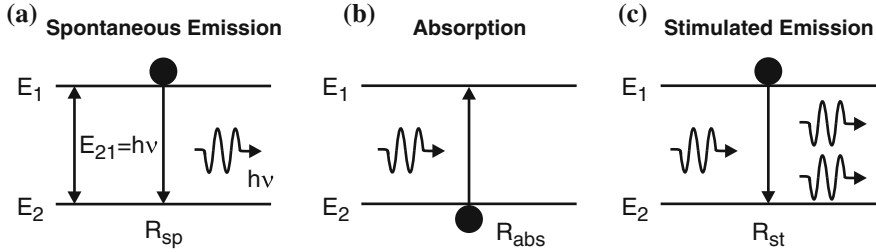


Fig. 2.1 Three fundamental electron-photon interactions in a radiative equilibrium. **a** An electron relaxes from the higher energy level resulting in the spontaneous emission of a photon with the energy of $h\nu$; **b** absorption; and **c** stimulated emission

is the frequency of the photon. This process is called spontaneous emission. Second, an electron at the energy level E_2 can absorb a photon with the energy E_{21} and move to the higher energy state E_1 . Finally there is the phenomena of *stimulated emission* postulated by Albert Einstein. A photon with the energy E_{21} stimulates an electron at the energy level E_1 to move to the lower energy level E_2 by emitting a photon of the exact same energy, wavelength, direction, impulse, polarization and phase as the initial photon. Thus the incident and the emitted photon are coherent. A laser makes use of the stimulated emission in order to create emission of coherent photons. Each of these processes has its own rate, which are R_{sp} , R_{abs} , and R_{st} for the spontaneous emission, absorption, and stimulated emission, respectively. The three fundamental electron photon interactions are illustrated in Fig. 2.1.

Spontaneous emission can only occur if electrons populate the higher energy level E_1 . Thus R_{sp} is proportional to the electron concentration N_1 at the energy level E_1 . Thus one can write:

$$R_{sp} = A_{sp} \cdot N_1 \quad (2.1)$$

where A_{sp} is the proportionality factor of the spontaneous emission. At least one photon is required in order to enable absorption and stimulated emission. Since absorption requires electrons in the lower energy level E_2 and stimulated emission requires electrons at the higher energy-level E_1 , the rates for the absorption R_{abs} and for the stimulated emission R_{st} are proportional to the electron concentrations N_2 and N_1 , respectively. Since both processes require incident photons, both rates are also proportional to the light intensity Φ . Thus the rates for the absorption and the stimulated emission can be written as:

$$R_{abs} = B_{abs} \cdot N_2 \cdot \Phi, \quad (2.2)$$

$$R_{st} = B_{st} \cdot N_1 \cdot \Phi, \quad (2.3)$$

where B_{abs} and B_{st} are the proportionality factors of the absorption and the stimulated emission, respectively. A_{sp} , B_{abs} , and B_{st} are called the Einstein coefficients for

the spontaneous emission, absorption, and the stimulated emission, respectively. Absorption means annihilation of photons whereas the effects of spontaneous and stimulated emission create photons. In a radiative equilibrium the number of photons remains constant, thus the annihilation and creation processes balance each other and thus:

$$R_{abs} = R_{sp} + R_{st}. \quad (2.4)$$

2.1.2 Population Inversion

In a semiconductor laser the effect of stimulated emission is employed to create coherent light emission with a large optical power. Thus the stimulated emission is desired to be as large as possible for efficient light amplification. In other words the goal is a positive net optical gain. The derivation of the condition for a positive net optical gain is explained in Ref. [2] and only the conclusions are given here. In an equilibrium the ratio of the electron concentration at the higher energy level to that of the lower energy level, thus N_1/N_2 can be expressed by Boltzmann statistics. Inserting the blackbody radiation intensity spectrum and making use of Eq. 2.4 yields the conclusion that for all temperatures:

$$B_{abs} = B_{st}. \quad (2.5)$$

Because of Eq. 2.5 the Einstein coefficients B_{abs} and B_{st} will in the following simply be called B . When the semiconductor laser diode is operated in the laser mode the contribution of the spontaneous emission to the coherent light emission is very small and can therefore be neglected, as is also done in several assumptions in Sect. 3.1. Then the stimulated emission is considered to be the only photon creation process and the absorption remains the only photon annihilation process and the net stimulated emission rate is simply the difference between the rate of these two processes and is given by:

$$R_{st} - R_{abs} = (N_1 - N_2) \cdot B \cdot \Phi. \quad (2.6)$$

Net light amplification is realized when R_{st} is larger than R_{abs} , thus when $N_1 > N_2$. In an equilibrium more electrons will be in the lower energy level E_2 than at the level of E_1 and therefore $N_1 < N_2$. The case of $N_1 > N_2$ is called *population inversion* and is one prerequisite for lasing. A schematic of a population inversion and the principle of light amplification via stimulated emission is shown in Fig. 2.2. As shown in [2], population inversion can not be achieved in an equilibrium. Thus the system needs to be pumped with energy from outside of the system. This pumping can be realized optically by photons of the energy $E_{21} = h\nu$. One big advantage of semiconductor lasers is the ability to use electrical pumping that allows a very small

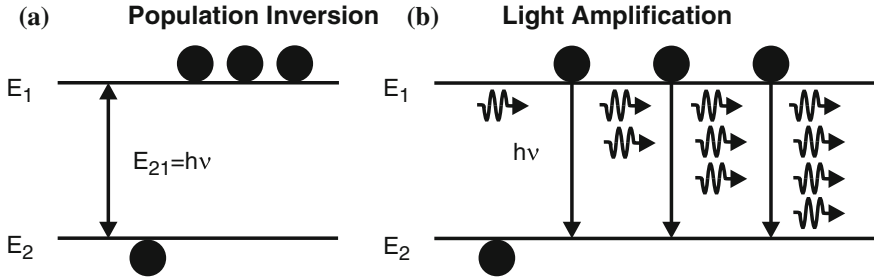


Fig. 2.2 **a** In a population inversion, more electrons are in the energy-level E_1 than in the energy-level E_2 , thus $N_1 > N_2$. **b** An incident photon of the energy $h\nu$ enables light amplification by stimulated emission

device footprint on the order of micrometers. Then the population inversion can be realized by forward biasing a pn-junction laser diode structure. The basic operation principles of semiconductor laser diodes are discussed in the following section.

2.1.3 Population Inversion in Semiconductor Laser Diodes

Semiconductor lasers are a key enabling technology for many applications that impact our daily life. A detailed review of the development of semiconductor lasers can be found in Ref. [3]. In semiconductor lasers the population inversion is more complex than explained in the previous section. In principle the upper and lower energy levels E_1 and E_2 are the lowest conduction and highest valence bands of the semiconductor material that serves as the active material. Thus in a semiconductor laser diode E_1 and E_2 can then be named as E_{CB} and E_{VB} , respectively. At room temperature or elevated ambient temperatures not all electrons are in the lowest energy levels and the closely spaced energy levels form a continuum of energy levels called an energy band. In a bulk 3D semiconductor interband transitions from upper band to lower band energy levels must also be considered. Thus energy bands exist in bulk semiconductors and not single discrete energy levels, and as a result a range of energy transitions corresponding to different absorption and emission energies are possible.

The energy-difference of the lowest conduction band and the highest valence band is the band gap energy E_g . Thus the energy $E_{21} = h\nu$ must be E_g and the wavelength of the stimulated emission is determined by the E_g of the active semiconductor material.

An electron-hole pair, instead of a single electron, interacts in a semiconductor laser with the photon(s). Thus in a semiconductor laser the stimulated emission rate R_{st} is not only proportional to the probability (f_1) of electrons in the conduction band, but also to the probability of unoccupied states in the valence band ($1 - f_2$), the probability of existing holes. In other words an electron and a corresponding hole

have to exist in order to enable stimulated emission. The same is true for spontaneous emission. For the absorption of a photon with an energy of $h\nu = E_g$ empty states at the energy level E_1 have to exist, which is given by $(1 - f_1)$. Thus the rates of the spontaneous emission, absorption, and stimulated emission in a semiconductor material change to:

$$R_{sp} = A_{sp} \cdot f_1(1 - f_2), \quad (2.7)$$

$$R_{abs} = B \cdot f_2(1 - f_1) \cdot \Phi, \quad (2.8)$$

$$R_{st} = B \cdot f_1(1 - f_2) \cdot \Phi. \quad (2.9)$$

The condition for population inversion in a semiconductor material is derived in the same way as previously in the general case and is explained in detail in Refs. [4, 5]. Using Eq. 2.5 and again neglecting spontaneous emission, the expression for the net photon generation rate in the semiconductor is similar to Eq. 2.6 derived for the general case:

$$R_{st} - R_{abs} = (f_1 - f_2) \cdot B \cdot \Phi. \quad (2.10)$$

In semiconductor material the occupation probabilities f_1 and f_2 are described using the Fermi-Dirac statistics. Thus f_1 and f_2 become for nondegenerately-doped semiconductors [4]:

$$f_1 = \frac{1}{e^{(E_{CB} - E_{F,CB})/k_B T} + 1}, \quad (2.11)$$

$$f_2 = \frac{1}{e^{(E_{VB} - E_{F,VB})/k_B T} + 1} \quad (2.12)$$

where $E_{F,CB}$ and $E_{F,VB}$ are the conduction and valence band quasi-Fermi levels, k_B is the Boltzmann constant and T is the temperature. Assuming that the spontaneous emission can be neglected, a net stimulated emission occurs when the stimulated emission rate R_{st} is larger than the rate R_{abs} of the absorption. Thus for a net stimulated emission the ratio of R_{st} to R_{abs} must be larger than 1:

$$\frac{R_{st}}{R_{abs}} > 1. \quad (2.13)$$

The ratio of R_{st} and R_{abs} as given in Eqs. 2.8 and 2.9 is:

$$\frac{R_{st}}{R_{abs}} = \frac{B \cdot f_1(1 - f_2) \cdot \Phi}{B \cdot f_2(1 - f_1) \cdot \Phi}. \quad (2.14)$$

The Einstein coefficient B and Φ cancel each other out and writing $(E_{CB} - E_{VB})$ as E_g and $(E_{F,CB} - E_{F,VB})$ as ΔE_F yields:

$$\frac{R_{st}}{R_{abs}} = \frac{f_1(1 - f_2)}{f_2(1 - f_1)} = e^{(\Delta E_F - E_g)/k_B T}. \quad (2.15)$$

Thus the condition (2.13) is true and a net stimulated emission can be achieved when:

$$(\Delta E_F - E_g) > 0 \Rightarrow \Delta E_F > E_g. \quad (2.16)$$

According to Eq. 2.16 the quasi-Fermi level separation must be larger than the bandgap energy E_g . This can be achieved for a doped semiconductor pn-junction diode when a forward voltage is applied. The quasi-Fermi level separation is proportional to the applied forward voltage. Thus there exists a minimum voltage that needs to be applied to create the population inversion that is necessary for net stimulated emission, e.g. net optical gain. This minimum voltage depends on the doping concentration of the semiconductor material and the band gap E_g .

2.1.4 Laser Cavity

To increase the stimulated emission rate, mirrors are used to confine the photons in a cavity such that they pass several times through the active region before leaving the laser. High mirror power reflectances eventually lead to high light intensities Φ inside the cavity which according to Eq. 2.9 gives rise to the stimulated emission rate R_{st} . Each photon that is created via stimulated emission increases the light intensity Φ .

In general mirror cavities define resonant laser modes via the condition for standing waves. For planar cavities such as a “Fabry-Perot” cavity only those wavelengths can lase which fulfill the following condition for constructive interference:

$$L = \frac{\lambda}{2}m \quad (2.17)$$

where L is the cavity length, e.g. the distance between the two mirrors, and m is an integer. Thus if L is large compared to λ , many laser modes will be allowed. As can also be seen in Eq. 2.17 when setting, $m = 1$ the shortest possible cavity length L is half the wavelength. For most lasers, even most semiconductor laser diodes, L is much larger than the wavelength λ leading to hundreds or thousands of possible lasing wavelengths, e.g. longitudinal modes.

Electrically pumped semiconductor laser diodes are the smallest practical lasers. The length of edge emitting laser diodes is on the order of 100s of micrometers. Still this length allows many modes. Since in vertical-cavity surface-emitting lasers the cavity lengths are defined by the epitaxial growth instead of by cleaving waferspices it is relatively simple to realize lasers with the shortest possible optical cavity length of $L = \lambda/2$. As will be discussed later such a short cavity length has several advantages among which a smaller mode volume is one of the most important, leading to potentially higher modulation bandwidth and more energy-efficient operation. The epitaxial design of 980-nm VCSELs with a short $\lambda/2$ -cavity and measurement results of these VCSELs are presented later in this dissertation in Sect. 6.2 and Chap. 8, respectively.

In a real semiconductor laser diode additional effects such as the nonradiative recombination of electron-hole pairs need to be taken into account. These effects result from electrons that interact with other electrons or phonons and experience an energy transfer without the creation of photons. The two main nonradiative recombination effects in semiconductor lasers are Auger-effects and recombination at defects, interfaces, and surfaces, and can be represented by a common nonradiative recombination lifetime τ_{nr} and rate R_{nr} . One main prerequisite for minimizing nonradiative recombination is a high crystalline quality with low defect densities. But also the quality of the semiconductor processing can have an impact on R_{nr} , for instance rough semiconductor sidewalls. Because nonradiative recombination is a loss that increases the required minimum pump energy to achieve lasing, R_{nr} should be as small as possible. The goal of minimizing R_{nr} is accounted for in the epitaxial design of the laser and to a great extent is determined by the epitaxial material used in the active region of the laser diode.

Photons that are created via stimulated emission can stimulate the creation of further photons as well as increase the light intensity Φ . Thus the emission of one stimulated photon will eventually result in the stimulated emission of many equal photons. In a real semiconductor the above-mentioned losses exist. While stimulated emission (no matter whether population inversion is reached or not) is an optical gain free carrier absorption and optical scattering are potential loss terms. In general the gain and loss is not homogenous in the laser cavity, thus both vary with the position in the cavity. Because light amplification is desired the light intensity Φ should increase with each roundtrip of the photons within the cavity. Assuming that the gain and loss are distributed homogeneously within a one-dimensional (1D) cavity the dependence of Φ on the distance z (counted from the position of the initial photon creation) can be expressed as [2, 4]:

$$\Phi(z) \propto e^{(g-\alpha)z} \quad (2.18)$$

where g is the optical gain and α is the optical loss of the cavity. Thus α includes absorption as well as scattering losses, and other losses of the cavity. Considering a complete roundtrip in a cavity between two mirrors with power reflectance values of R_1 and R_2 , the intensity Φ has been increased if the following condition is fulfilled [2, 4]:

$$R_1 R_2 e^{(g-\alpha)2L} > 1 \quad (2.19)$$

where L is again the 1D cavity length. After a complete roundtrip $2 \cdot L$ all losses and gains have been experienced twice. At each mirror a fraction $(1 - R_1)$ or $(1 - R_2)$ of the light is transmitted through the respective mirror, leaves the cavity and thus can also be considered to be a loss that must be compensated by the gain. Thus in order to amplify the light intensity the condition (2.19) can be rewritten in the following form where the gain equals the losses [2, 4]:

$$g_{th} = \alpha + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) = \alpha + \alpha_m \quad (2.20)$$

where g_{th} is the threshold gain for lasing and α_m is the mirror loss. In case the gain inside the cavity is smaller than g_{th} no lasing can be achieved. In order to achieve lasing a maximum allowed mirror loss α_m is given by Eq. 2.20 leading to minimal required values of R_1 and R_2 , respectively.

In general semiconductor lasers do not always have gain along the entire cavity length, e.g. the light travels in regions inside the cavity where it may experience losses but not gain. Typically edge-emitting laser diodes have gain in larger fractions of the cavity length L . While in edge-emitting semiconductor lasers the light travels in parallel to the active layers with gain, the light propagates perpendicular to these layers in VCSELs. Thus while edge-emitting laser diode designs exist where the light can experience gain in the complete length L of the cavity, this is not possible for VCSELs. Therefore VCSELs have typically a much shorter gain length as compared to edge-emitting laser diodes. The gain length in VCSELs is simply the accumulated thickness of the quantum wells (QWs). As is shown in Sect. 6.2 the accumulated thickness of five QWs of the 980-nm VCSELs presented in this dissertation is 20 nm. For simple edge-emitting semiconductor lasers the gain length can be as long as the cavity and is thus on the order of several 100s of μm . Due to the very short gain length in VCSELs its mirror loss has to be very small in order to achieve lasing. Thus the power reflectance of a simple semiconductor/air interface of $\sim 30\%$ is by far not large enough for VCSELs which require mirrors with a power reflectance approaching 100%. Such high power reflectances can be achieved with distributed Bragg reflectors (DBRs) as explained in the next section.

2.2 Confinement of Light and Current in VCSELs

The present state-of-the-art VCSEL designs incorporate many different design features in order to enable error-free operation at large bit rates. Two of the most important *building blocks* that are used by the presently fastest and most efficient VCSELs are all semiconductor distributed Bragg reflectors (DBRs) that confine the light in the longitudinal direction and oxide-apertures for transverse optical and current confinement. Although there exists a great degree of freedom in designing different DBRs and oxide-apertures, the basic principle and functionality of these two important VCSEL building blocks remain the same and are explained in the following sections.

2.2.1 Distributed Bragg Reflectors

Due to the small length of material with gain inside the cavity of typically only tens of nanometers, the mirror loss α_m has to be very small for VCSELs in order to reach

threshold gain g_{th} as given by Eq. 2.20. This is usually realized by using distributed Bragg reflectors (DBRs) which can easily achieve power reflectance values close to 100%.

In present VCSELs typically semiconductor and dielectric DBRs are used for confining the light in the longitudinal direction. These mirrors can be modified in different ways by using extra layers, varying the layer thicknesses or material compositions, or etching parts of the layers and thus creating symmetric or nonsymmetric lateral patterns such as for example rings, circles [6–9], or photonic crystals. High-contrast gratings (HCGs) [10–12] can theoretically completely or partly replace DBRs, but to date the dynamic performance of HCG VCSELs is not comparable to that of modern VCSELs with semiconductor DBR mirrors. Also the processing of HCGs is very challenging and requires electron beam lithography and an extremely good control of all process parameters. Thus wafer-scale fabrication of thousands or millions of HCG VCSELs with is neither practical nor cost-efficient. Therefore epitaxially-grown high crystalline quality semiconductor DBRs remain the preferred choice for cost-efficient large wafer-scale VCSEL fabrication.

DBR mirrors are based on the fundamental principal of reflection and transmission of light at interfaces of two different materials having two different refractive indices. At any interface part of the light is transmitted and part of it is reflected. In the following analysis absorption of light and scattering losses are neglected, thus the intensity Φ of the transmitted and of the reflected light add up to the initial intensity of the incident light. Then the fraction of the reflected light is given by the power reflectance R (a value between 0 and 1) and the fraction of the transmitted light is given by the transmittance $T = (1 - R)$. If n_0 is the real refractive index of the first material and n_1 the real refractive material of the second material, then the reflectance for normal incidence as shown in Fig. 2.3a is given by:

$$R_0 = \left(\frac{n_0 - n_1}{n_0 + n_1} \right)^2. \quad (2.21)$$

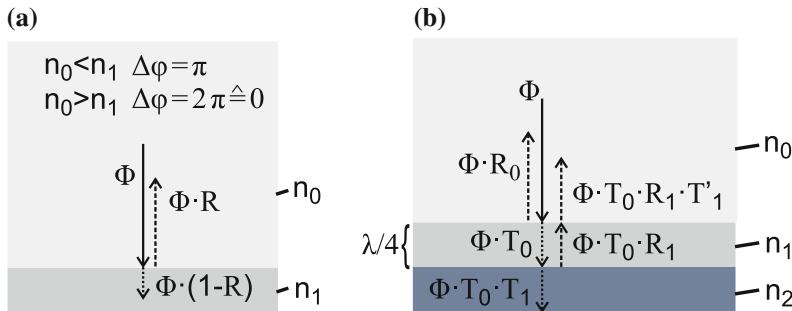


Fig. 2.3 **a** Reflection and transmission of the light intensity Φ at the interface of two materials with different real refractive indices n_0 and n_1 for normal incidence. **b** Reflection and transmission for light intensity at a three-layer system for normal incidence. Not all possible light rays are shown

Adding a third material significantly increases the complexity of reflection and transmission of the light, because multiple transmitted and reflected light rays exist. Incident light of the intensity Φ gets reflected at the interface of the materials with refractive indices n_0 and n_1 . Light with the intensity of $R_0 \cdot \Phi$ is reflected and the fraction $T_0 \cdot \Phi$ is transmitted and hits the second interface of the materials characterized by the refractive indices n_1 and n_2 , respectively. Again reflection and transmission occur. The transmittance is T_1 , thus the transmitted intensity is $T_1 \cdot T_0 \cdot \Phi$. The reflected intensity is $R_1 \cdot T_0 \cdot \Phi$ and experiences transmission and reflection at the interface between the materials with refractive indices n_1 and n_0 , respectively. The intensity $\Phi \cdot T_0 \cdot R_1 \cdot T_1'$ is transmitted to the material with the refractive index n_0 and can now interfere with the first reflected light. The different reflected and transmitted light intensities in a system with three layers of different refractive index is schematically shown for normal incidence in Fig. 2.3b.

Multiple reflections occur in a multilayer system as shown in Fig. 2.3b, and thus a large number of light rays exist that all interfere with each other. In general the interference will increase or decrease the intensity of the resulting light ray, depending on the phase values of the interfering rays. The two extreme cases are constructive and destructive interference, where the light intensities add up, or the light intensity becomes 0. Constructive interference occurs between two rays when their phase difference $\Delta\varphi$ is 0 (or 2π) and destructive interference occurs for a phase difference of π . Two different effects lead to a phase-change $\Delta\varphi$. The phase-change $\Delta\varphi$ due to propagation along the geometric distance d of light with the wavelength λ through a medium with the real refractive index n is:

$$\Delta\varphi = \frac{2\pi}{\lambda} d \cdot n. \quad (2.22)$$

The product $d \cdot n$ of the geometrical distance d and the real refractive index n is called the *optical thickness*. For a phase-change of 2π , equivalent to 0, thus no change of the phase, the optical thickness must equal the wavelength λ . For an optical thickness of $\lambda/2$ the phase difference $\Delta\varphi$ becomes π . The phase of the light can also experience a change when it is reflected at an interface of materials with two different refractive indices as depicted in Fig. 2.3a. When the incident light gets reflected at the interface of the two materials with refractive indices of n_0 and n_1 a phase shift of π occurs when $n_0 < n_1$ and there is no phase shift for $n_0 > n_1$. Taking into account the two effects causing the phase of the light to shift, one can derive the conditions for constructive and destructive interference of the reflection at an optically-thick $\lambda/4$ layer depicted in Fig. 2.3b. Two reflections at different interfaces resulting in two different reflected beams need to be considered. Because the layer with the refractive index of n_1 has an optical thickness of $\lambda/4$, the phase change of the beam that is reflected at the second interface between materials with refractive indices of n_1 and n_2 experiences a phase shift of π for propagating through the $\lambda/4$ -layer twice. Thus for $n_0 > n_1 > n_2$ the phase difference of the two beams will be π leading to destructive interference. The case of $n_0 < n_1 < n_2$ leads to destructive interference as well, because both reflected beams experience a phase shift of π due

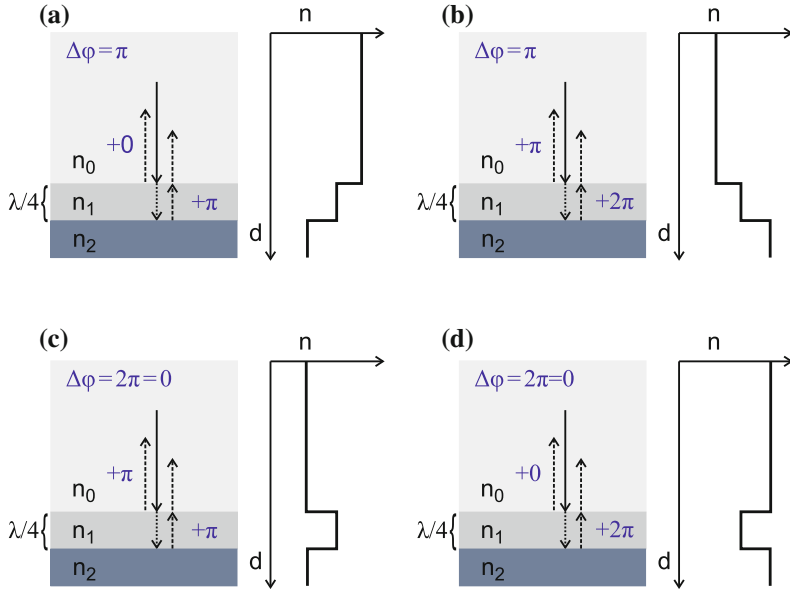


Fig. 2.4 Phase difference $\Delta\varphi$ between incident and reflected light for reflection at a $\lambda/4$ -layer and different combinations of the refractive indices n_0 , n_1 , and n_2 . In the case of **a** $n_0 > n_1 > n_2$ and **b** $n_0 < n_1 < n_2$, the resulting phase difference caused by propagation and reflection is π leading to destructive interference. For **c** $n_1 > n_0, n_2$ and **d** $n_1 < n_0, n_2$ the phase difference $\Delta\varphi$ is 2π which is equivalent to zero and thus the light will experience constructive interference

to the reflection. The phase-shift of π caused by the round trip through the $\lambda/4$ -thick layer has to be added to the second beam, resulting in a phase difference $\Delta\varphi = \pi$ between the two beams. In case the refractive index of the $\lambda/4$ -layer is larger than those of the other two layers, a phase change of π occurs at the first reflection at the interface of the first medium and the $\lambda/4$ -layer and the light that is reflected at the second interface of the materials with n_1 and n_2 experiences a phase change of π for propagating through the $\lambda/4$ -layer. Thus the resulting phase difference is $\Delta\varphi = 2\pi = 0$. If the refractive index of the $\lambda/4$ -layer is smaller than the other two, there will be a phase change of π due to reflection at the interface n_1/n_2 and in addition there is the same phase change due to propagating the optical distance of $\lambda/2$. Thus the resulting phase difference $\Delta\varphi$ will be 0 leading to constructive interference. The resulting phase differences $\Delta\varphi$ for the four different combinations of the n_0 , n_1 , and n_2 values are shown in Fig. 2.4a–d.

The simplest DBR consists of a stack of alternating layers of two different materials with different real refractive indices n_1 and n_2 . Thus relative to each other one material has a higher refractive index and the other has a lower refractive index. The difference between these two refractive indices is the refractive index contrast Δn . In most cases it is desirable to have a large refractive index contrast Δn in case this does not cause other drawbacks such as an increased electrical resistance or a low

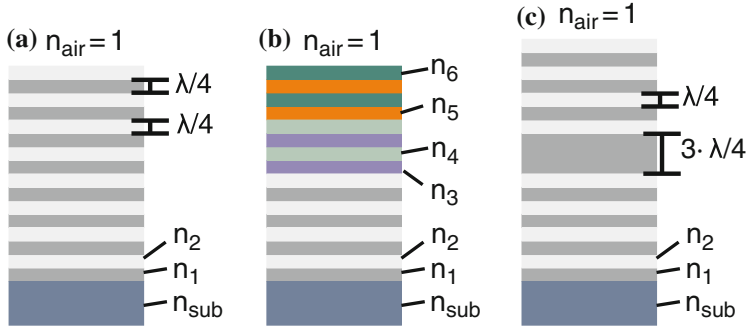


Fig. 2.5 Schematics of distributed Bragg reflector (DBR) structures placed onto a substrate and having air on the top. **a** All DBR mirror pairs are the same, **b** more than two different refractive indices are used in the DBR stack, and **c** one additional $\lambda/2$ -thick optically inactive layer is inserted

heat conductance. The optical thickness of each layer is $n \cdot d = \lambda_0/4$, where n is the real refractive index, d the geometric layer thickness, and λ_0 is the wavelength in freespace or vacuum. Because the refractive index varies with the wavelength λ_0 , the mirror layer has an optical thickness $\lambda/4$ for only one design target wavelength λ_0 . In the following examples absorption and other losses such as scattering are neglected and all calculations are performed for the case of normal incidence.

A schematic of a simple DBR with eight DBR pairs of materials with real refractive index values of n_1 and n_2 placed onto a substrate taken to be infinitely thick with a real refractive index of n_{sub} is shown in Fig. 2.5a. The incident medium above the DBR mirror is assumed to be air taken to be infinitely thick with a real refractive index of $n_{air} = 1$. More complex DBR structures can exist of more than two different materials as indicated in Fig. 2.5b showing an example with six different materials all having an optical thickness of $\lambda/4$. In general a DBR can also contain layers with an optical thickness that is different from $\lambda/4$. For example optically inactive layers with an optical thickness that is an integer multiple of $\lambda/2$ can be inserted into any DBR mirror without changing the power reflectance at the design wavelength λ_0 of the DBR as shown in Fig. 2.5c. Assuming that no losses like absorption occur in the optically inactive additional $\lambda/2$ -thick (“absentee”) layer the power reflectance at the design wavelength λ_0 of the structures shown in Fig. 2.5a, c is therefore the same. The top and bottom DBRs of the 980-nm VCSEL designs presented in this dissertation employ optically inactive GaAs-layers in order to facilitate current spreading and heat dissipation as discussed in Sect. 6.2.

For simple DBR structures as shown in Fig. 2.5a consisting only of alternating $\lambda/4$ layers the power reflectance value at normal incidence for the Bragg design wavelength can easily be calculated using the following equations. The power reflectance R_{2N} of a simple DBR for alternating $\lambda/4$ layers with the refractive indices n_1 and n_2 placed onto a substrate with the refractive index n_{sub} and having air on the other side of the DBR is given for normal incidence by the following equation for an even number $2N$ of DBR pairs:

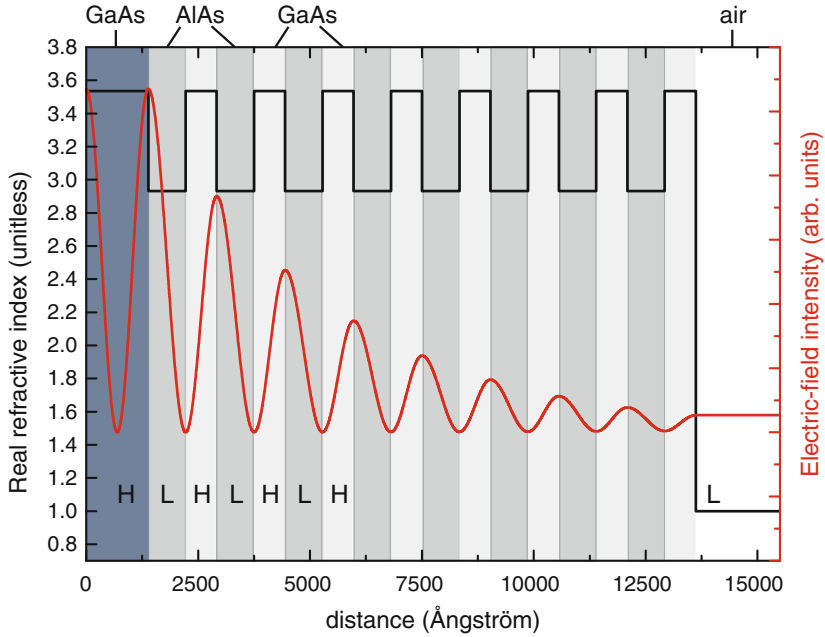


Fig. 2.6 Real refractive index and the electric field intensity profile for an 8-period distributed Bragg reflector (DBR) with eight equal DBR pairs. The substrate has the same real refractive index as the high refractive index layers of the DBR. *H* and *L* indicate the relative high and low real refractive index layers of the DBR. Light is incident from the GaAs substrate to the right toward air

$$R_{2N} = \left| \frac{n_{sub} (n_2/n_1)^{(2N)} - 1}{n_{sub} (n_2/n_1)^{(2N)} + 1} \right|^2 \quad (2.23)$$

where *N* is the integer number of DBR pairs (periods). For an uneven number $(2N+1)$ of DBR pairs the reflectivity $|r_{2N+1}|^2$ is given by:

$$R_{2N+1} = \left| \frac{n_1^2 (n_1/n_2)^{(2N)} - n_{sub}}{n_1^2 (n_1/n_2)^{(2N)} + n_{sub}} \right|^2. \quad (2.24)$$

For more general and complex DBR structures or complete VCSEL designs the power reflectance values and spectra and electric field intensity profiles are calculated using the software POLYMORPH [13]. All of the following DBR examples are designed for a wavelength of 980-nm. The refractive index profile and the electric field intensity of the simple DBR structure of Fig. 2.5a are plotted in Fig. 2.6. The plotted real refractive indices of n_{sub} and n_2 correspond to GaAs and n_1 corresponds to AlAs, all at a wavelength of 980-nm. The electric field intensity is calculated for incident light from the GaAs-substrate. The amplitude of the electric field intensity slowly

decays in the 8 DBR pairs having a local maximum at each interface between the high refractive index GaAs and the low refractive index AlAs. A certain amplitude of the electric-field intensity leaves the mirror on the right side into the air with a refractive index of 1. The power reflectance R at 980-nm calculated with POLYMORPH is 94.51 % ($R = 0.9451$).

The electric field intensity profile in the DBR structure shown in Fig. 2.5b looks similar to that of the structure in Fig. 2.5a. In contrast to the DBR stack in Fig. 2.6, the first top DBR pairs have been replaced with DBR pairs with a smaller refractive index contrast Δn as compared to the first case where binary AlAs/GaAs-DBR pairs are used. As an example the top two DBR pairs are formed by $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}/\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ and the third and fourth DBR pairs are formed by $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$. Thus the refractive index contrast Δn differs for different pairs of the DBR as do the geometric layer thicknesses in order to keep the optical thicknesses equal to $\lambda/4$. The refractive index contrast Δn is 0.6 for the first four binary AlAs/GaAs mirrors counted from the GaAs-substrate and reduces to 0.46 and 0.33 for the following ternary $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -DBR pairs. In the second example DBR in Fig. 2.7 the difference of the electric field intensity as compared to the all

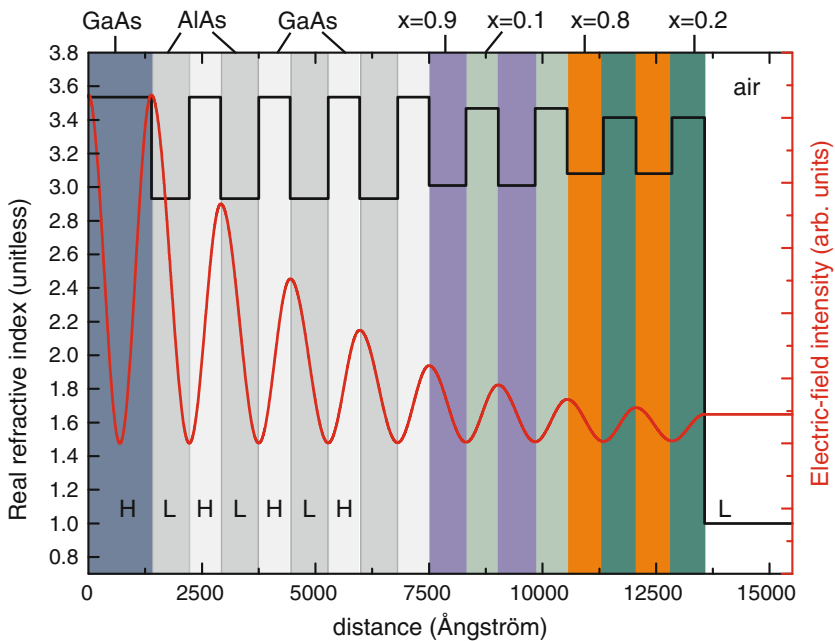


Fig. 2.7 Real refractive index and the electric field intensity profile for a distributed Bragg reflector (DBR) with eight DBR pairs. The substrate has the same real refractive index as the high refractive index layers of the DBR. The first four DBR pairs are the same as in Fig. 2.6, followed twice by 2 periods with decreasing refractive index contrast. H and L indicate the relative high and low real refractive index layers of the DBR

binary DBR seems not to be very large. The second DBR with the same number of DBR pairs but with 4 DBR pairs with smaller Δn has a smaller power reflectance of 90.94 % ($R = 0.9094$) at 980-nm. The electric field intensity and the refractive index profile of the DBR structure with varying refractive index contrast is shown in Fig. 2.7.

The third example DBR is a purely binary layer DBR where the high refractive index layer of the fourth DBR period has an optical thickness of $(3\lambda)/4$ instead of $\lambda/4$. The additional $\lambda/2$ layer of GaAs is optically inactive with respect to the power reflectance at the design wavelength of the DBR, thus the relative maximum amplitude of the electric field intensity does not change within the $\lambda/2$ -thick layer leading to a second peak of the exact same amplitude. Each layer with an optical thickness of an integer multiple of $\lambda/2$ is optically inactive (if absorption is zero) and adds additional electric field intensity peaks. Thus a layer with the thickness of $d = n \cdot \lambda/2$ will have n additional peaks of the electric field intensity, all of the same amplitude. The electric field intensity and the refractive index profile of the DBR structure with an inserted extra $\lambda/2$ -thick GaAs-layer are shown in Fig. 2.8.

At the design wavelength λ_0 of 980-nm both binary DBR mirrors with and without the extra $\lambda/2$ -layer yield the same phase and power reflectance. The more the

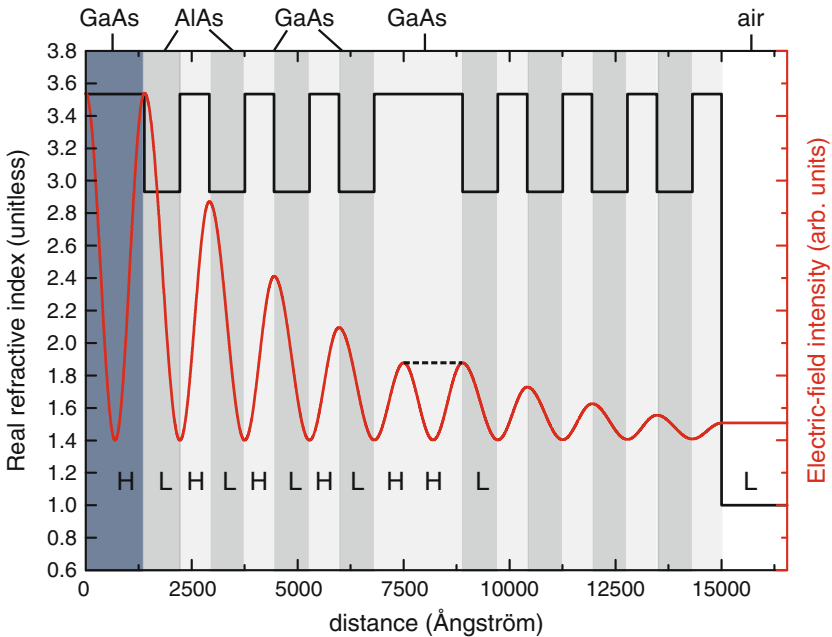


Fig. 2.8 Real refractive index and the electric field intensity profile for a distributed Bragg reflector (DBR) with eight DBR pairs. The substrate has the same real refractive index as the high refractive index layers of the DBR. The optical thickness of the high refractive index layer of the fourth DBR pair is $\lambda/2$ thicker than $\lambda/4$. H and L indicate the relative high and low real refractive index layers of the DBR

wavelength deviates from the design wavelength the extra layer becomes a larger deviation from the periodicity as compared to the DBR without the extra $\lambda/2$ layer, resulting in a decrease of the power reflectance. For application in VCSELs it is desired that the DBR functions as a high reflectance mirror in a broader range of wavelengths, thus the power reflectance versus the wavelength is of importance. The width of the DBR stop band can be used to compare DBR power reflectance spectra. The stop band width is defined as the width between the two wavelengths at which the DBR power reflectance has dropped to 90%. Of the three presented 8-period DBRs, the all binary DBR with all layers having an optical thickness of $\lambda/4$ achieves the broadest band width of 88 nm which reduces to 75 and 35 nm for the DBR with an extra $\lambda/2$ layer and for the DBR with the variation in the refractive index contrast, respectively. Due to the lower average refractive index contrast of the DBR with different Δn but the same number of periods also the maximum power reflectance at the design wavelength is lower than that of the two different AlAs/GaAs-DBRs. Because the mean refractive index contrast at the design wavelength remains unchanged when introducing an extra $\lambda/2$ -layer the power reflectance at this wavelength also does not change. For the other wavelengths this extra layer is not of the optical thickness of $\lambda/2$ and thus further reduces the reflectance for these wavelength. As a consequence the width of the DBR stop band reduces when inserting an extra $\lambda/2$ -layer. The calculated reflectance spectra of the three different 8-period DBR mirrors are shown in Fig. 2.9.

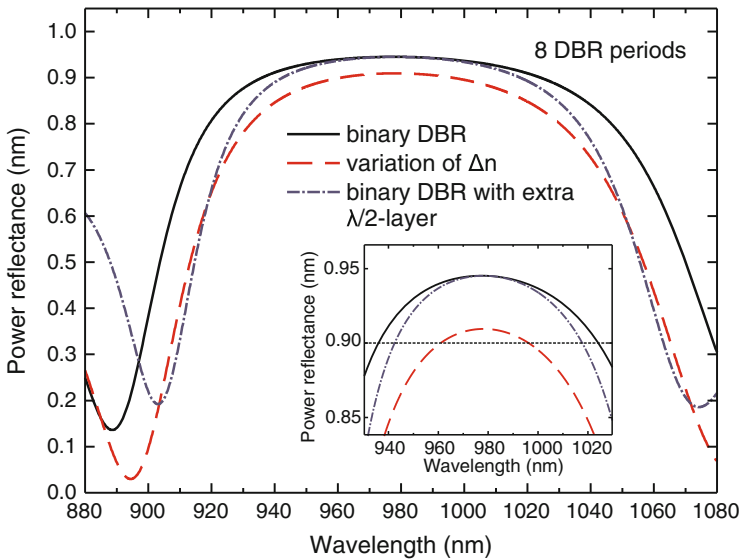


Fig. 2.9 Calculated power reflectance versus wavelength at normal incidence for three $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -DBR structures with 8 periods. The *inset* shows a zoomed-in plot of the spectra demonstrating the different widths of the stop band of the DBR with a design wavelength of 980-nm

Extra $\lambda/2$ -layers or layers with an optical thickness of an integer multiple of $\lambda/2$ can serve various purposes and are often used as contact layers in VCSELs with intra-cavity or intra-DBR contacts [14]. Parts of these layers will then be highly doped to facilitate lateral current transport. In order to avoid absorption the high doping concentrations will be positioned at the antinodes, e.g. at the minima, of the electric field intensity. Thus $n \cdot \lambda/2$ -thick layers ($n = 1, 2, 3, \dots$) allow us to add more highly doped material into the DBR without affecting the power reflectance at the design wavelength λ_0 . These added absentee layers may also be used to facilitate current spreading inside the DBRs in VCSELs where the current is injected from contact layers below and above the bottom and top DBR, respectively.

The stop band width of the DBR decreases with increasing number of inserted $\lambda/2$ -layers. For the given binary AlAs/GaAs example DBR with 8 periods in Fig. 2.6, the width of the stop band is 88 nm without any additional $\lambda/2$ -layers and decreases to 75, 68, 57, and 43 nm for 1, 2, 4, and 8 inserted $\lambda/2$ -layers, respectively, where each single additional $\lambda/2$ -layer is added to separate high refractive index GaAs-layers. In the last case of 8 extra $\lambda/2$ -layers each high refractive index layer of the DBR has an extra $\lambda/2$ of GaAs. The calculated power reflectance spectra for binary AlAs/GaAs-DBRs with different numbers of $\lambda/2$ -layers and a design wavelength of 980-nm are plotted in Fig. 2.10.

Instead of inserting separate $\lambda/2$ -layers to several separate DBR pairs, one can also add layers that have an optical thickness of an integer multiple of $\lambda/2$ to a single DBR pair. This also changes the power reflectance spectra. Compared to

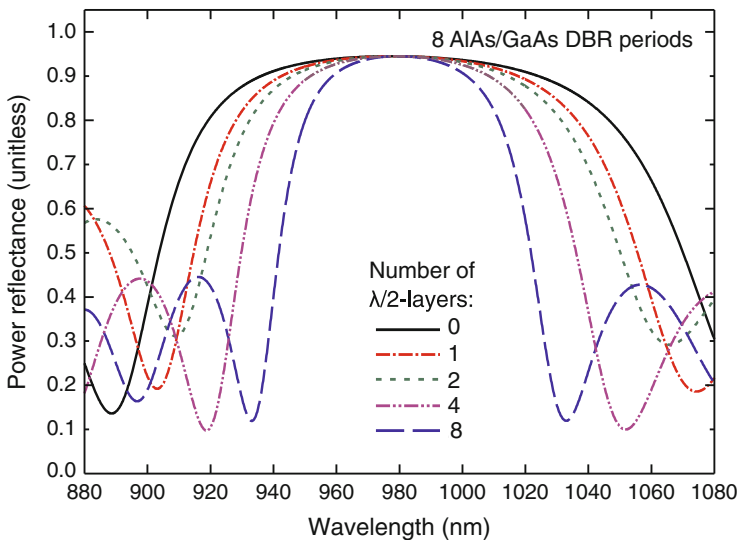


Fig. 2.10 Calculated power reflectance versus wavelength at normal incidence for binary AlAs/GaAs DBRs with 8 periods and 0, 1, 2, 4, and 8 additional $\lambda/2$ GaAs-layers with a design wavelength of 980-nm

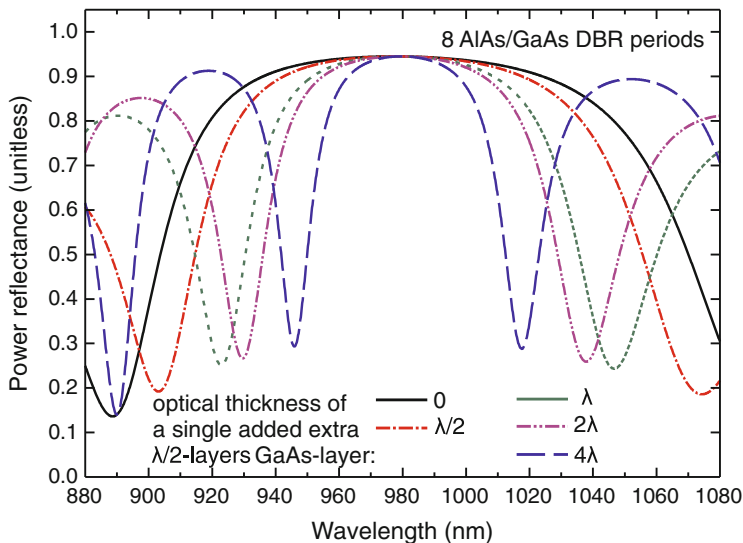


Fig. 2.11 Calculated power reflectance versus wavelength for binary AlAs/GaAs DBRs with 8 periods with and one without an added GaAs layer with an optical thickness of $\lambda/2$, λ , 2λ , and 4λ

DBRs where single $\lambda/2$ layers are added to separate DBR pairs, adding a single layer of the same accumulative optical thickness of the individual $\lambda/2$ -layers, leads to different power reflectance spectra. The power reflectance remains unaffected at the Bragg design wavelength, but the width of the stop band reduces with increasing optical thickness and the maximum power reflectance of the sidelobes of the DBR significantly increase with increasing optical thickness of the added layers. Thus while having the same optical thickness at the design wavelength the impact on the power reflectance spectra of the DBRs is different for adding several separate $\lambda/2$ -layers or one thick layer with the same accumulative optical thickness. As previously stated the width of the stop band is 88 and 75 nm without and with a single $\lambda/2$ -layer. It further reduces to 65, 51, and 35 nm for an optical thickness of λ , 2λ , and 4λ , respectively. In the case of the 4λ optically thick additional GaAs-layer, one sidelobe of the DBR reaches a maximum power reflectance value of 91.28 % at a wavelength of 919 nm. This sidelobe was not included in the determination of the stop band width. The power reflectance spectra for AlAs/GaAs DBRs with 8 periods without extra $\lambda/2$ -layer and with extra layers of the optical thickness of $\lambda/2$, λ , 2λ , and 4λ are shown in Fig. 2.11.

Due to the periodic nature of the DBR mirrors large power reflectance values can be achieved by simply increasing the number of DBR pairs. For an infinite number of DBR pairs the power reflectance at the Bragg wavelength λ_0 approaches 100 %. The required number of DBR pairs in order to achieve a given reflectance value at λ_0 decreases with increasing refractive index contrast of the two materials used for the $\lambda/4$ -layers. The $\text{Al}_x\text{Ga}_{1-x}\text{As}$ material system is well-suited and widely used for

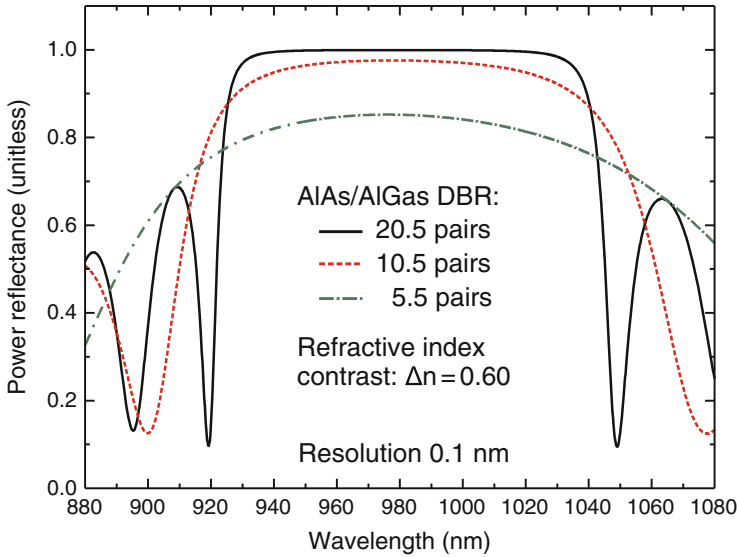


Fig. 2.12 Calculated power reflectance versus wavelength at normal incidence for three binary AlAs/GaAs-DBR structures on a GaAs substrate with 5.5, 10.5, and 20.5 DBR periods and with air as the incident medium

VCSELs emitting at 850 and 980-nm. The maximum refractive index contrast Δn in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -system is achieved for mirrors consisting of binary AlAs/GaAs-DBR pairs and is $\Delta n = 0.60$ at a wavelength of 980-nm. Although the DBR layers of a given design will be only for one wavelength of the exact optical thickness of $\lambda/4$, the resulting reflectance spectrum shows a broader so-called stop band providing high values of power reflectance for wavelengths shorter and longer than the design wavelength λ_0 of the DBR. The power reflectance versus the wavelength for binary AlAs/GaAs-DBRs with 5.5, 10.5, and 20.5 DBR pairs is shown in Fig. 2.12. The maximum power reflectance value increases with increasing number of DBR pairs and a flat stop band is formed when the number of DBR pairs is large (more than ~ 20 periods). The stop band with a maximum power reflectance given as a percentage of 99.94 % and a stop band width of 113 nm can clearly be seen for the mirror with 20.5 DBR pairs. The width of the stop band is determined at the distance between the two wavelengths at which the power reflectance reaches 90 % as done previously for the DBR examples with 8 mirror pairs. The calculated power reflectance values given as a percentage at 980-nm are 97.57 and 85.19 % for the DBRs with 10.5 and 5.5 DBR pairs, respectively. The width of the stop band is 107 nm for the DBR with 10.5 DBR pairs and is not given for the mirror with only 5.5 pairs, because this DBR does not achieve reflectance values of 90 %.

In a VCSEL both mirrors typically have to achieve power reflectance values close to 100 % to enable lasing. At 980-nm a DBR consisting of 25.5 pairs of binary AlAs/GaAs $\lambda/4$ pairs achieves a calculated power reflectance of 99.99 % with a stop

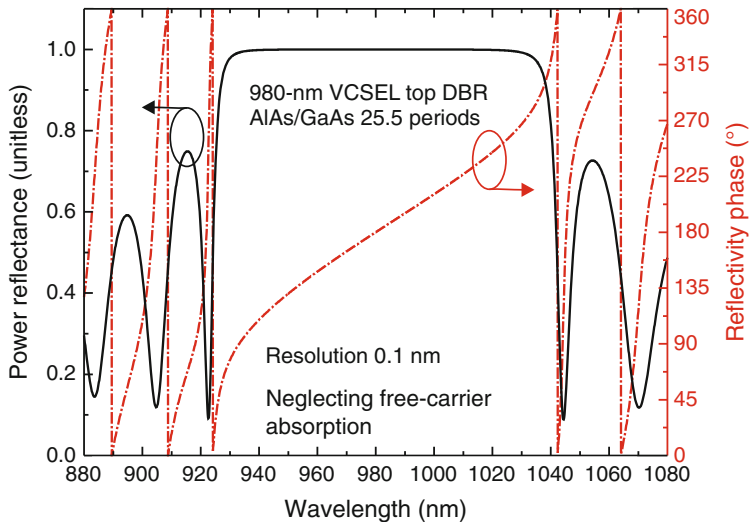


Fig. 2.13 Calculated power reflectance and reflectivity phase spectrum for an AlAs/GaAs DBR on a GaAs substrate with 25.5 mirror pairs and with air as the incident medium

band width of 112 nm. By adding more DBR pairs the power reflectance can not significantly increased anymore, because the limit of 100% can only be theoretically achieved by an infinite number of DBR pairs. Thus one simply adds more 9s behind the comma of the power reflectance by further adding DBR pairs. The power reflectance and the reflectivity phase of a DBR with 25.5 AlAs/GaAs $\lambda/4$ pairs and a design wavelength λ_0 of 980-nm are plotted versus the wavelength in Fig. 2.13.

The saturation behavior of the power reflectance of a DBR can be shown by removing material from the top of the DBR, modeling the power reflectance R and plotting R versus the thickness of the removed material or equivalently versus the etch depth from the top DBR surface. The power reflectance versus etch-depth shows an oscillating behavior and reaches local maxima when a complete DBR period is removed and local minima when a $\lambda/4$ layer is completely removed as shown in Fig. 2.14. The difference of two neighbor local maxima increases with increasing etch-depth. This is equivalent to the fast increase in power reflectance when DBR pairs are added to a DBR with a low number of periods and the saturation of the power reflectance once the power reflectance reaches values above approximately 90% ($R = 0.90$).

The power reflectance of the DBR stop band increases with the refractive index contrast Δn and with the number of the DBR pairs. For a larger Δn the power reflectance increases faster with increasing number of periods. The power reflectance at the design wavelength is plotted for different refractive index contrasts Δn of 0.60, 0.46, and 0.33 versus the number of DBR pairs in Fig. 2.15 and the power reflectance for 25.5 DBR pairs of the given Δn values is plotted versus the wavelength in

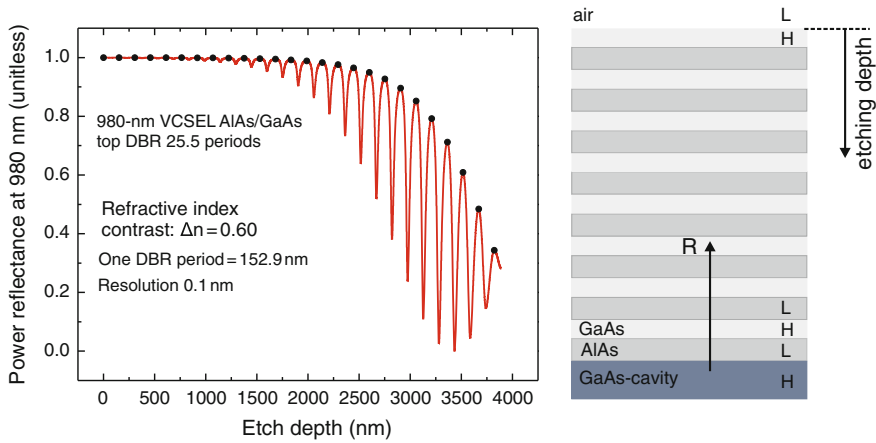


Fig. 2.14 Calculated power reflectance R normal incidence at 980-nm versus the etch depth of an AlAs-DBR with 25.5 mirror pairs. The R is as seen by photons in the cavity looking up through the DBR toward air

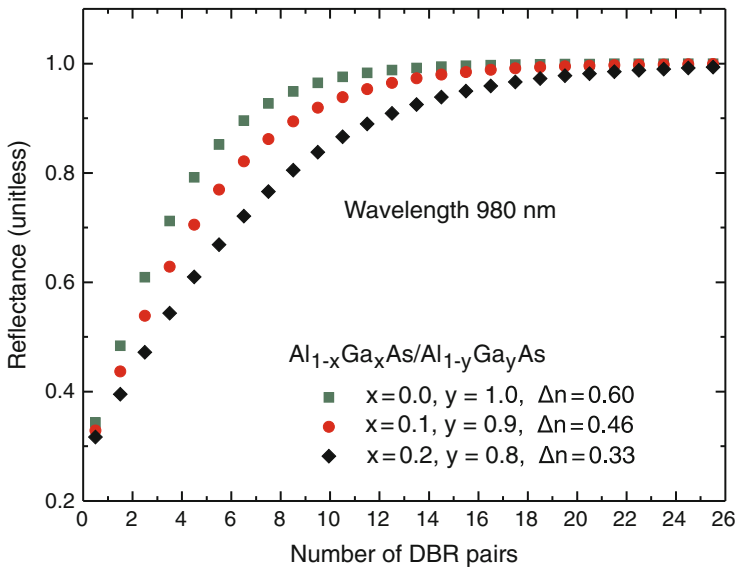


Fig. 2.15 Calculated power reflectance R at normal incidence versus the number of distributed Bragg reflector pairs for $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -DBRs with different refractive index contrasts Δn

Fig. 2.16. For 25.5 DBR pairs the maximum power reflectance at the design wavelength of 980-nm is 99.99, 99.91, and 99.34 % and the width of the stop band is 112, 75, and 63 nm for a refractive index contrast of 0.60, 0.46, and 0.33, respectively.

So far only single DBRs have been considered. In order to build a cavity two DBRs are required, one on each side of the active optical cavity region that contains

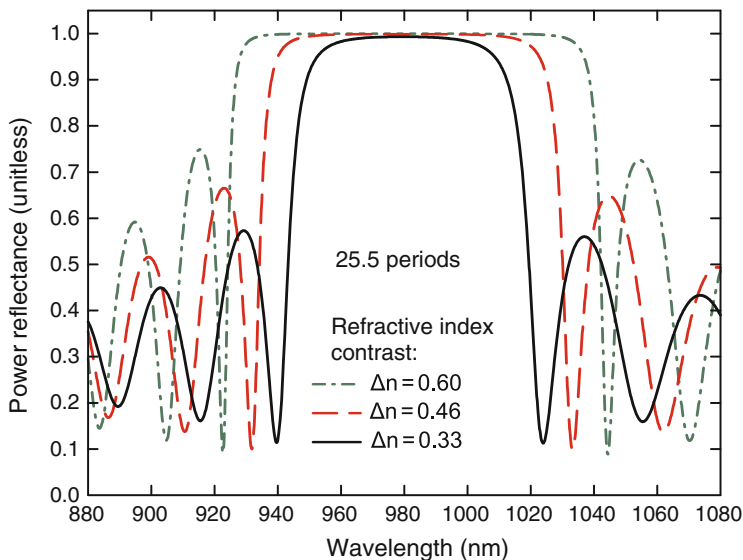


Fig. 2.16 Calculated power reflectance R at normal incidence from air as the incident medium versus the wavelength of 25.5 $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -DBR pairs with different refractive index contrasts Δn

the gain material. The shortest possible cavity-length has an optical thickness of $\lambda/2$. The 980-nm VCSEL design that is presented in this dissertation in Chap. 6 has a short $\lambda/2$ -cavity to improve the dynamic properties of the VCSEL. Although in real VCSEL structures the active region in between the DBRs typically consists of different material compositions including the quantum wells or quantum dots, barrier layers, compositionally-graded or abrupt separate confinement heterostructure layers, etc., an average real refractive index can be determined that represents the materials in the cavity for the modelling of the electric field intensity. The optical thickness of course remains constant. In the model only the physical thickness of the material with the calculated average real refractive index has to be adjusted accordingly. In a $\lambda/2$ optically-thick cavity the electric field intensity has an anti-node (peak) in the center of the cavity, when the average real refractive index of the optical cavity is lower than the real refractive of the neighbor layers [15]. The active material, such as the quantum wells, are then typically placed at the position where the maximum of the electric field intensity is achieved. Compared to a longer $3\lambda/2$ -cavity the overlap of the gain material and the electric field intensity can be increased via a $\lambda/2$ -cavity [16] which is advantageous for the overall VCSEL properties, especially for achieving large modulation bandwidths. The placement of five quantum wells relative to the maximum of the electric field intensity in a $\lambda/2$ -cavity is shown for the 980-nm VCSEL presented in this dissertation in Fig. 6.4 in Chap. 6.

The real refractive index and the electric field intensity versus the distance from the wafer surface for a passive (i.e. without optical gain) multilayer asymmetric

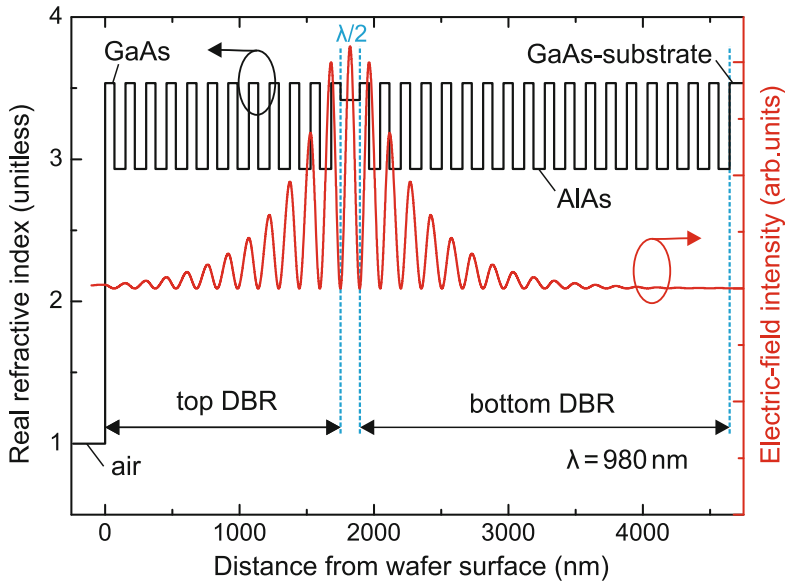


Fig. 2.17 Real refractive index and the normalized electric field intensity versus the distance from the top epitaxial surface of a 980-nm passive etalon with binary GaAs/AlAs distributed Bragg reflectors and a $\lambda/2$ -cavity on a GaAs-substrate. Light at 980-nm (modeled as plane waves) is incident from air looking down onto the passive multilayer asymmetric etalon. The light is reflected and also passes through the etalon exiting into the GaAs substrate

etalon formed by binary GaAs/AlAs-DBRs with a $\lambda/2$ -cavity are shown in Fig. 2.17. Air is assumed above the top DBR and the structure is placed onto a GaAs-substrate. Both the air and the GaAs-substrate are assumed to have an infinite thickness. The top-DBR and bottom DBR consist of 11.5 and 18 binary GaAs/AlAs DBR pairs, respectively. For the design wavelength of 980-nm, this structure is resonant leading to the increase of the electric field intensity towards the center of the cavity structure.

Multiple nonabsorbing absentee layers that are optically inactive for the design wavelength can be added to the etalon structure to serve different purposes such as to function as current spreading layers or intracavity ohmic contact layers. Because only the optical thickness matters, these absentee layers can be of the same low or high refractive index as the used $\lambda/4$ -layers of the DBR material or in general it can have any other real refractive index. Figure 2.18 shows the same structure from Fig. 2.17 but with a $5 \times \lambda/2$ optically-thick GaAs absentee layers added to the top DBR and a $3 \times \lambda/2$ optically-thick AlAs-layer placed within to the bottom DBR. These layers are not optical cavities, because the maxima of the electric field intensity of the neighbor layers are lower and higher, respectively. The absentee layers do not lead to the building up of the electric field intensity as is the case for a resonant optical cavity. An SEM image of a VCSEL structure with three absentee layers, two close to the active region and one closer to the wafer surface is shown in Fig. 2.19.

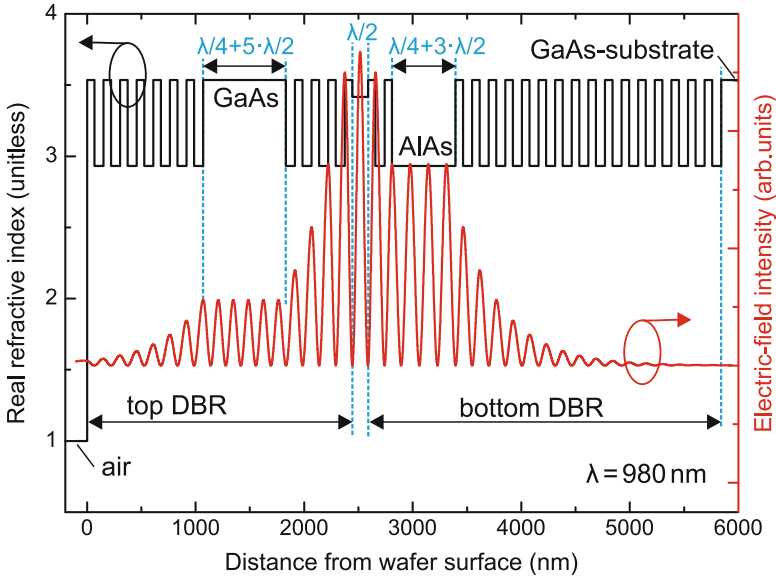


Fig. 2.18 Real refractive index and the normalized electric field intensity versus the distance from the top epitaxial surface of a 980-nm passive etalon with binary GaAs/AlAs distributed Bragg reflectors (DBRs) and a $\lambda/2$ -cavity on a GaAs-substrate. The top and bottom DBR each contain absentee layers with an optical thickness of a multiple of $\lambda/2$

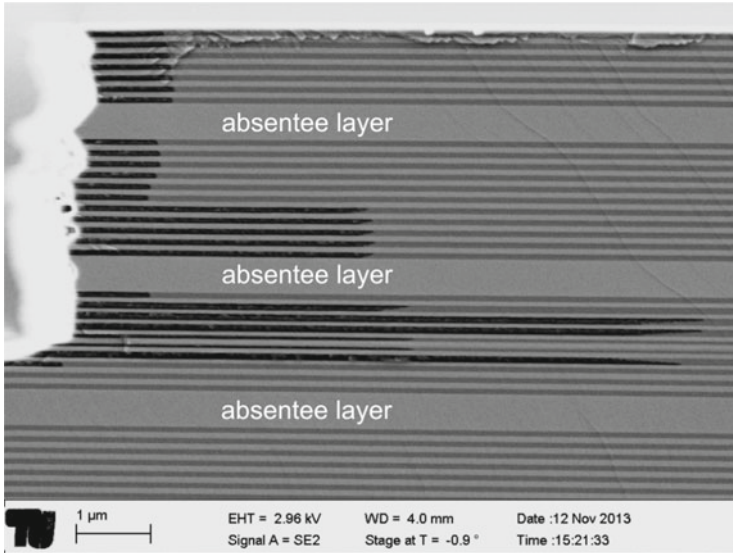


Fig. 2.19 Scanning electron microscope (SEM) image of a 980-nm VCSEL structure with three absentee layers

In addition to the optical properties such as power reflectance and reflectivity phase, also the thermal conductance and the electrical resistance are important for the CW and dynamic VCSEL properties. In order to reduce the mirror resistance, abrupt interfaces between the high and low refractive index materials can be replaced with different kinds of material compositional gradings. The simplest grading would be a linear grading from the low refractive index material to the high index material or vice versa. The doping is also very important for achieving a low mirror resistance. High doping levels are used only at the nodes of the electric field intensity in order to avoid free-carrier absorption losses which lead to heat creation in the DBRs. The emission wavelength of the VCSEL also limits the choice of possible materials or material compositions for the DBR, because of the wavelength dependance of the real refractive index and the absorption. For example GaAs can not be used as a mirror material for 850-nm VCSELs, because it absorbs all light at wavelengths shorter than about 870-nm. At 980-nm GaAs is transparent and can therefore be used in the DBRs of 980-nm VCSELs. Because of its high real refractive index and high thermal conductivity it is desirable to use GaAs-layers as the high refractive index material in DBRs. The 980-nm VCSEL design presented in Chap. 6 uses GaAs-layers as the high refractive index material in the top and bottom DBRs.

2.2.2 Oxide-Apertures in VCSELs

Distributed Bragg reflectors confine the light in the longitudinal direction, e.g. vertical to the wafer surface. In order to improve the static and dynamic VCSEL properties a transverse optical confinement is required as well. This can be realized by simply etching a mesa as schematically shown in Fig. 2.21a. The disadvantages of such a simple approach is that non-radiative surface recombination can occur at the etched sidewalls of the mesa and that relatively large bias currents are required to reach lasing threshold, because a large area needs to be pumped. Thus it is desired to realize transverse optical and current confinement to enable efficient laser operation and low laser threshold currents.

Many different approaches for achieving transverse optical and current confinement in VCSELs exist, each with its own specific advantages and draw backs. Oxide-layers formed by the selective wet-oxidation of aluminum-rich $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers [17] have many applications in semiconductor lasers [18]. Such oxide-layers formed by oxidation of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers were first used in edge-emitting lasers and then soon applied in VCSELs in 1994 [19] as current confining layers in oxide-confined VCSELs. Choquette et al. demonstrated the first oxide-confined VCSEL with conducting all semiconductor DBRs in the same year, which is the first VCSEL technology similar to the VCSELs presented in this dissertation. Oxide-confinement has led to a significant reduction in the threshold current [20] and increase of the wallplug efficiency of VCSELs [21, 22] and finally also enabled the presently fastest VCSELs.

Oxide-layers in VCSELs are formed by the wet oxidation at high temperatures of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers with a high aluminum-content [17, 18, 23]. The formation

of the oxide-apertures is typically performed at temperatures higher than 350°C in a saturated $\text{N}_2/\text{H}_2\text{O}$ atmosphere. The oxide-apertures of the VCSELs presented in this dissertation were formed at 420°C as explained in Chap. 5. The oxidation rate of aluminum-rich $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers depends on many different parameters, such as the aluminum-content, the layer thickness, crystalline quality, doping, material composition and doping of the neighbor layers, the temperature and other parameters. Thus very accurate control of the thickness and material composition is required during the epitaxial growth to successfully realize (multiple) oxide-aperture layers. Binary AlAs is easier to epitaxially grow with a guaranteed material composition as compared to for example $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with $x = 0.98$ where the exact aluminum-content can only be realized with a certain maximum accuracy. Even a small deviation from the desired aluminum-content impacts the oxidation rate significantly [23]. In present state-of-the-art high-speed VCSELs typically $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ -layers are employed that form the oxide-apertures during the oxidation process [24–27]. A slightly lower aluminum-content of 98 % is used instead of binary AlAs, in order to reduce the strain induced by shrinkage of the oxidized layers [23] as compared to the non-oxidized layers. The shrinkage reduces with decreasing aluminum-content and is about 12–13 % for oxidized AlAs [23]. A different approach is to remove oxide-layers via selective chemical wet etching [28] in order to form air gaps and thus remove the majority of the strain. The strain induced by the oxide-layers is critical for the lifetime of the VCSELs. Because oxide-layers are typically placed close to the active region in order to effectively confine the current in the region with gain, the geometric distance to the active region is relatively small. Thus any defects that might be created at the tip or along the length of a strained oxide layer will eventually propagate to the active region and therefore drastically reduce the lifetime of the VCSEL. In order to reduce the strain of the oxidized layers, the thickness of the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ -layers prior to the oxidation is typically chosen to be between 20 and 30 nm [24, 25, 27]. Due to differences in the oxidation rates for different crystal axis, the oxide-aperture for a circular mesa can deviate from a circular shape. Thus square oxide-apertures are possible depending on the epitaxial layer design and the conditions during the wet oxidation, even for round mesa structures. Top views of oxide-aperture test structures are shown in Fig. 2.20a, b. Oxidized layers in a DBR structure with different oxidation depths are shown in a cross section scanning electron microscope (SEM) image and a schematic illustrating the application of such oxidation layers in a VCSEL mesa are shown in Fig. 2.20c, d, respectively.

Oxide-apertures can simultaneously provide optical and current confinement. The oxidized and non-oxidized $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers differ in the refractive index, where the selectively oxidized material has a low refractive index of ~ 1.6 [23]. Thus there is a lateral refractive index profile leading to lateral optical confinement and the formation of modes. The impact of the oxide-layers on the optical properties of the VCSEL depends on the number, thickness, and position of the oxide-layers. Simultaneously the oxide-layers serve as current-blocking layers forcing the current to flow through the oxide-aperture where the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layer is not oxidized and which has typically a much smaller diameter than the etched mesa. This allows one to achieve high current densities at comparably low bias currents. Schematic cross

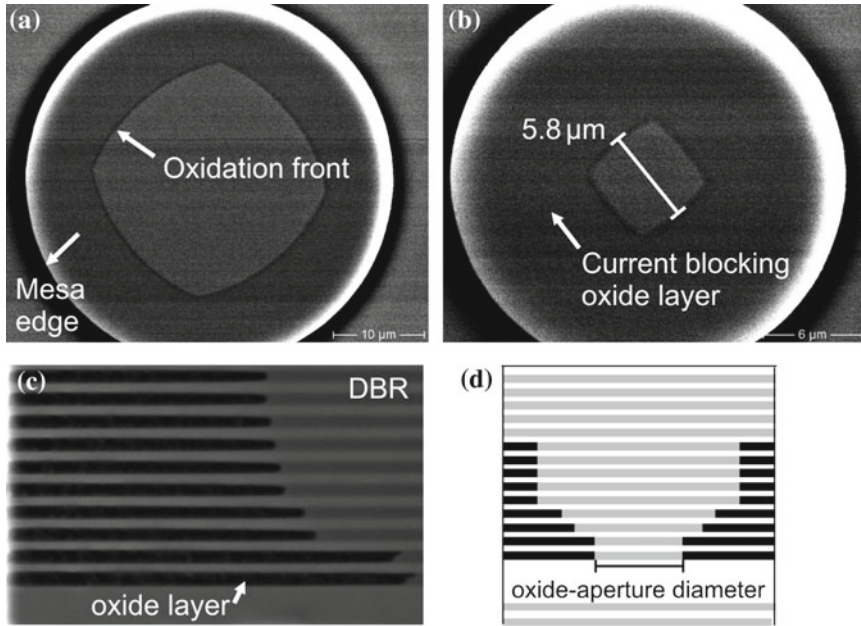


Fig. 2.20 Scanning electron microscope (SEM) image of oxidation test structures. The oxidized aluminum-rich $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers can be seen under a thin GaAs cap layer for a **a** $41\text{ }\mu\text{m}$ mesa diameter **b** and $24\text{ }\mu\text{m}$ mesa diameter test structure. **c** SEM image of a cross section of oxidized $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers. **d** Schematic of a mesa structure with deep oxidation and oxide-aperture layers of different lengths

sections of a VCSEL and the current flow with and without oxide-confinement is shown in Fig. 2.21a, b, respectively.

For data transmission across long distances of multimode optical fiber a low spectral width at a simultaneously low current density is desired. The current density is directly related to the lifetime of the VCSELs and in order to realize reliable operation for commercial application the current density is desired to be below 10 kA/cm^2 [29]. The spectral width limits the maximum transmission distance across a particular type of MMF of a given modal bandwidth ($\text{GHz}\cdot\text{km}$) and a given attenuation (dB/km) as functions of wavelength [30, 31]. A small spectral width allows to transmit across longer distances of multimode fiber. Error-free operation of 850-nm single-mode VCSELs (side-mode suppression ratio $>40\text{ dB}$) has been demonstrated at 10 Gb/s up to a MMF transmission distance of a record-long 2820 m [32]. Typically the maximum transmission distance of single-mode VCSELs across MMF is limited by the relatively small output power of the VCSEL and the attenuation of the fiber. Thus many approaches of increasing the output power of the VCSEL while maintaining the single-mode emission have been investigated.

Without any other further modification the diameters of the optical and current aperture are the same. Thus several approaches have been developed to add addi-

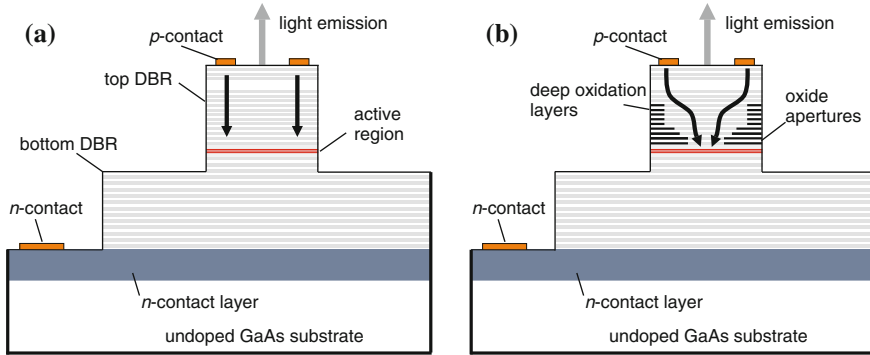


Fig. 2.21 Schematic cross section of top-emitting VCSELs with doped semiconductor top and bottom distributed Bragg reflectors **a** without oxide-apertures and **b** with current confining multiple oxide-apertures and deep oxidation layers. The thick black arrows indicate the difference of the current flow in the two structures

tional transverse optical confinement or laterally varying losses to a VCSEL in order to modify the spectral width. The main approaches are photonic crystals (PhC) [33] where vertical holes are etched into the top DBR in order to modify the effective index or surface relief structures of different geometries which introduce mode selective losses [6, 8, 34]. Both approaches have led to an increase of single-mode output power [8] and an increase of the multimode optical fiber distance at simultaneously lower current density [9, 35], but both approaches also share the need for additional processing steps with a high precision, which might be cost-inefficient and detrimental for mass production and commercialization. Photonic crystals and surface reliefs typically introduce additional losses which is detrimental for energy-efficient data transmission. In this dissertation extremely energy-efficient data transmission across long distances of MMF is demonstrated with oxide-confined VCSELs without any further modification of the top DBR. While the bit rate and MMF distance is comparable to those results obtained with PhC and surface relief VCSELs, the energy efficiency is much better without additional modification of the top DBR [36].

In addition to oxide-aperture layers, deep-oxidation layers [37] can be used to reduce parasitic capacitances and thus increase the electrical bandwidth of VCSELs for optical interconnects. Deep oxidation layers are $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers which have a lower oxidation rate and thus a shorter oxidation-depth than the layer(s) that form the oxide-aperture(s). Since the oxidation rate depends on both the aluminum content as well as on the layer thickness [23], the deep-oxidation layers have either to be thinner than the oxide-aperture layers or have a lower aluminum-content than the layers that are designed to form the oxide-apertures. Figure 2.22 shows the SEM image of a cross section of an oxidized VCSEL waferpiece of the 980-nm design presented in this dissertation. The oxidized high aluminum-content layers can be seen (dark horizontal layers). This image is a zoom-in of the 980-nm VCSEL structure shown in Sect. 6.2 in Fig. 6.6 and shows six tapered deep oxidation layers of different thickness

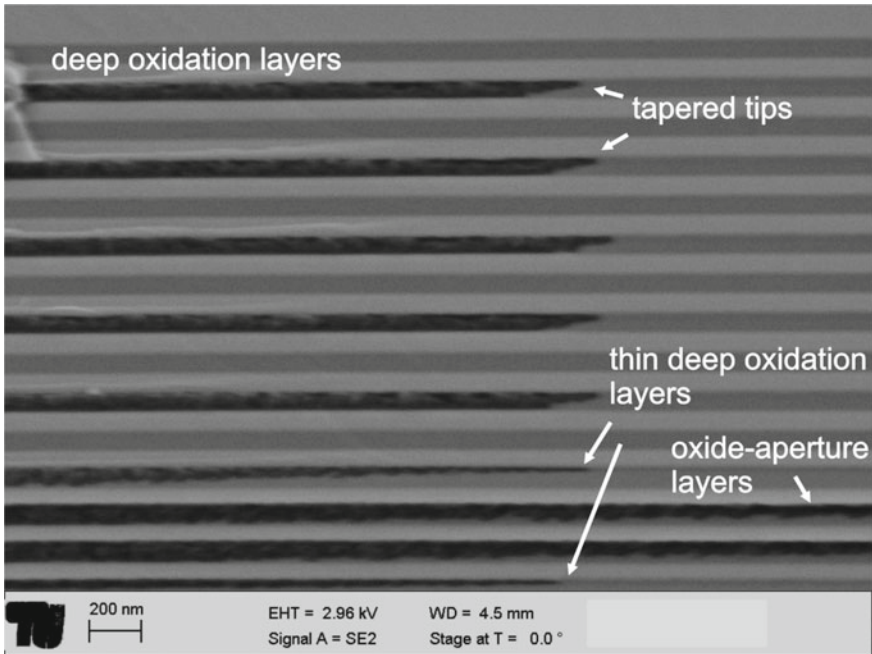


Fig. 2.22 Scanning electron microscope image of an oxidized 980-nm VCSEL wafer piece that was oxidized for 66 min at 420 °C at 50 mbar. Six deep oxidation layers are shown above two oxide-aperture layers

and different taper design, but with the same oxidation depth. The taper is realized by using a grading of the Al-content in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -layers. The design of the deep oxidation layers just above and below the two oxide-aperture layers is different, resulting in a much thinner tip of the oxidized layer due to the much longer taper. Oxide-aperture layers are typically tapered in order to decrease optical scattering losses [38].

For top-emitting VCSELs with epitaxially grown doped semiconductor DBRs, such as presented in this thesis, the top metal contact is usually designed in a circle, leaving the center of the topmost DBR layer free from metal. This contact shape leads to an inhomogeneous lateral current-density distribution inside the top DBR. In VCSELs with current-confining oxide-apertures, e.g. oxide-confined VCSELs, the oxide-aperture is typically smaller than the diameter of the top metal contact ring in order to prevent the metal contact from blocking and absorbing the light. This leads to current-crowding at the edge of the oxide-aperture where the current density is much higher than in the center of the conducting aperture, which may negatively impact the VCSEL performance by inhomogeneous heating resulting in a thermal lens or spatial hole burning. Current crowding is even a larger issue in VCSELs with intra-cavity contacts in which the vertical distance between the oxide-aperture layer and the layer in which the current is injected, is much smaller.

Because of the potential strain-induced reliability issues of oxide-confined VCSELs and the low heat conductance of the oxide-layers, the development of oxide-free VCSELs is a modern subject of research [39–41]. In such VCSELs the current apertures are lithographically defined and at least one etch and regrowth step is required. However the exact fabrication of such oxide-free VCSELs as well as the dynamic modulation properties have not been published. The published CW properties are very promising, because large optical output powers at small current-aperture diameters are achieved, for example 3 μm aperture-diameter devices achieve a maximum output power of 12 mW [40, 41], and the LI-curves are very insensitive to temperature changes. While the issue of the large differential resistance of small current-confining apertures remains unsolved, the achieved large photon densities might lead to large D-factors and the large output power at single-mode emission might enable longer MMF transmission distances at higher bit rates.

References

1. A. Einstein, Strahlungs-Emission und -Absorption nach der Quantentheorie. Verhandlungen der Deutschen Physikalischen Gesellschaft **18**, 318–323 (1916)
2. S.M. Sze, K.K. Ng, *Physics of Semiconductor Devices*, 3rd edn. (Wiley, Hoboken, 2006 and 2007)
3. D. Bimberg, From ugly duckling to radiant swan: half a century after the discovery of the semiconductor laser. IEEE Photonics Soc. News **27**(3), 4–9 (2013)
4. L.A. Coldren, S.W. Corzine, *Diode Lasers and Photonic Integrated Circuits*, Wiley Series in Microwave and Optical Engineering (Wiley, New York, 1995)
5. K.F. Brennan, *Introduction to Semiconductor Devices: For Computing and Telecommunications Applications* (Cambridge University Press, Cambridge, 2005)
6. H. Martinsson, J.A. Vukusic, M. Grabber, R. Michalzik, R. Jager, K.J. Ebeling, A. Larsson, Transverse mode selection in large-area oxide-confined vertical-cavity surface-emitting lasers using a shallow surface relief. IEEE Photonics Technol. Lett. **11**(12), 1536–1538 (1999)
7. J.S. Gustavsson, Å. Haglund, J. Bengtsson, P. Modh, A. Larsson, Dynamic behavior of fundamental-mode stabilized VCSELs using a shallow surface relief. IEEE J. Quantum Electron. **40**(6), 607–619 (2004)
8. Å. Haglund, J.S. Gustavsson, J. Vukusic, P. Modh, A. Larsson, Single fundamental-mode output power exceeding 6 mW from VCSELs with a shallow surface relief. IEEE Photonics Technol. Lett. **16**(2), 368–370 (2004)
9. E. Haglund, Å. Haglund, P. Westbergh, J.S. Gustavsson, B. Kögel, A. Larsson, 25 Gbit/s transmission over 500 m multimode fibre using 850 nm VCSEL with integrated mode filter. Electronics Letters **48**(9), 517–519 (2012)
10. Y. Zhou, M. Huang, C.J. Chang-Hasnain, Large fabrication tolerance for VCSELs using high-contrast grating. IEEE Photonics Technol. Lett. **20**(6), 434–436 (2008)
11. Y. Zhou, M. Huang, C. Chase, V. Karagodsky, M. Moewe, B. Pesala, F.G. Sedgwick, C.J. Chang-Hasnain, High-index-contrast grating (HCG) and its applications in optoelectronic devices. IEEE J. Sel. Top. Quantum Electron. **15**(5), 1485–1499 (2009)
12. M. Gebiski, M. Dems, J. Chen, Q.J. Wang, D.H. Zhang, T. Czynszanowski, The influence of imperfections and absorption on the performance of a GaAs/AIO high-contrast grating for monolithic integration with 980 nm GaAs-based VCSELs. J. Lightwave Technol. **31**(23), 3853–3858 (2013)
13. J.A. Lott, Polymorph, computer modeling software (unpublished), private communication (2015)

14. S. Imai, K. Takaki, S. Kamiya, J. Yoshida, Y. Kawakita, T. Takagi, K. Hiraiwa, H. Shimizu, T. Suzuki, N. Iwai, T. Ishikawa, N. Tsukiji, A. Kasukawa, Recorded low power dissipation in highly reliable 1060-nm VCSELs for green optical interconnection. *IEEE J. Sel. Top. Quantum Electron.* **17**(6), 1614–1620 (2011)
15. S.L. Chuang, *Physics of Photonic Devices*, 2nd edn., Wiley Series in Pure and Applied Optics (Wiley, Hoboken, 2009)
16. A. Mutig, D. Bimberg, Progress on high-speed 980nm VCSELs for short-reach optical interconnects. *Adv. Opt. Technol.* **2011**, 1–15 (2011)
17. J.M. Dallesasse, N. Holonyak, A.R. Sugg, T.A. Richard, N. El-Zein, Hydrolyzation oxidation of $Al_xGa_{1-x}As - GaAs$ quantum well heterostructures and superlattices. *Appl. Phys. Lett.* **57**(26), 2844 (1990)
18. J.M. Dallesasse, N. Holonyak, Oxidation of Al-bearing III-V materials: a review of key progress. *J. Appl. Phys.* **113**(5), 051101 (2013)
19. D.L. Huffaker, D.G. Deppe, K. Kumar, T.J. Rogers, Native-oxide defined ring contact for low threshold vertical-cavity lasers. *Appl. Phys. Lett.* **65**(1), 97–99 (1994)
20. K.D. Choquette, R.P. Schneider, K.L. Lear, K.M. Geib, Low threshold voltage vertical-cavity lasers fabricated by selective oxidation. *Electron. Lett.* **30**(24), 2043–2044 (1994)
21. K.L. Lear, K.D. Choquette, R.P. Schneider, S.P. Kilcoyne, K.M. Geib, Selectively oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency. *Electron. Lett.* **31**(3), 208–209 (1995)
22. J.M. Dallesasse, D.G. Deppe, III-V oxidation: discoveries and applications in vertical-cavity surface-emitting lasers. *Proc. IEEE* **101**(10), 2234–2242 (2013)
23. K.D. Choquette, K.M. Geib, C. Ashby, R.D. Twisten, O. Blum, H.Q. Hou, D.M. Follstaedt, B.E. Hammons, D. Mathes, R. Hull, Advances in selective wet oxidation of AlGaAs alloys. *IEEE J. Sel. Top. Quantum Electron.* **3**(3), 916–926 (1997)
24. P. Westbergh, R. Safaisini, E. Haglund, J. Gustavsson, A. Larsson, M. Geen, R. Lawrence, A. Joel, High-speed oxide confined 850-nm VCSELs operating error free at 40 Gbit/s up to 85 °C. *IEEE Photonics Technol. Lett.* **25**(8), 768–771 (2013)
25. P. Moser, P. Wolf, A. Mutig, G. Larisch, W. Unrau, W. Hofmann, D. Bimberg, 85 °C error-free operation at 38Gb/s of oxide-confined 980-nm vertical-cavity surface-emitting lasers. *Appl. Phys. Lett.* **100**(8), 081 103–1–3 (2012)
26. P. Westbergh, J.S. Gustavsson, B. Kögel, Å. Haglund, A. Larsson, A. Mutig, A.M. Nadtochiy, D. Bimberg, A. Joel, 40 Gbit/s error-free operation of oxide-confined 850 nm VCSEL. *Electron. Lett.* **46**(14), 1014–1015 (2010)
27. P. Moser, J.A. Lott, P. Wolf, G. Larisch, H. Li, D. Bimberg, Error-free 46 Gbit/s operation of oxide-confined 980 nm VCSELs at 85 °C. *Electron. Lett.* **50**(19), 1369–1371 (2014)
28. R.L. Naone, L.A. Coldren, Tapered air apertures for thermally robust VCL structures. *IEEE Photonics Technol. Lett.* **11**(11), 1339–1341 (1999)
29. B.M. Hawkins, R.A. Hawthorne, J.K. Guenter, J.A. Tatum, J.R. Biard, Reliability of various size oxide aperture VCSELs, in *52nd Electronic Components and Technology Conference*. IEEE, 28–31 May 2002, San Diego, CA, USA, pp. 540–550
30. D. Cunningham, P. Dawe, Review of the 10Gigabit ethernet link model: white paper: onids 2002. [Online], <http://www.avagotech.com/docs/AV02-2485EN>
31. D. Cunningham, P. Dawe, IEEE spreadsheet model (2001). [Online], http://www.ieee802.org/3/ae/public/email_attach/10GEPBud2_4_1.xls
32. G. Giaretta, R. Michalzik, A.J. Ritger, Long distance (2.8 km), short wavelength (0.85 mm) data transmission at 10Gb/sec over new generation high bandwidth multimode fiber, in *Lasers and Electro-Optics (CLEO) and the International Quantum Electronics Conference (IQEC)*, 7–12 May 2000, San Francisco, CA, USA, pp. 678–679
33. N. Yokouchi, A.J. Danner, K.D. Choquette, Two-dimensional photonic crystal confined vertical-cavity surface-emitting lasers. *IEEE J. Sel. Top. Quantum Electron.* **9**(5), 1439–1445 (2003)
34. J.A. Vukusic, H. Martinsson, J.S. Gustavsson, A. Larsson, Numerical optimization of the single fundamental mode output from a surface modified vertical-cavity surface-emitting laser. *IEEE J. Quantum Electron.* **37**(1), 108–117 (2001)

35. M.P. Tan, S.T.M. Fryslië, J.A. Lott, N.N. Ledentsov, D. Bimberg, K.D. Choquette, Error-free transmission over 1-km OM4 multimode fiber at 25 Gb/s using a single mode photonic crystal vertical-cavity surface-emitting laser. *IEEE Photonics Technol. Lett.* **25**(18), 1823–1825 (2013)
36. P. Moser, J.A. Lott, P. Wolf, G. Larisch, H. Li, D. Bimberg, 85-fJ dissipated energy per bit at 30 Gb/s across 500-m multimode fiber using 850-nm VCSELs. *IEEE Photonics Technol. Lett.* **25**(16), 1638–1641 (2013)
37. Y.C. Chang, C.S. Wang, L.A. Johansson, L.A. Coldren, High-efficiency, high-speed VCSELs with deep oxidation layers. *Electron. Lett.* **42**(22), 1281 (2006)
38. B.J. Thibeault, E.R. Hegblom, P.D. Floyd, R. Naone, Y. Akulova, L.A. Coldren, Reduced optical scattering loss in vertical-cavity lasers using a thin (300 Å) oxide aperture. *IEEE Photonics Technol. Lett.* **8**(5), 593–595 (1996)
39. X. Yang, M. Li, G. Zhao, Y. Zhang, S. Freisem, D.G. Deppe, Oxide-free vertical-cavity surface-emitting lasers with low junction temperature and high drive level. *Electron. Lett.* **50**(20), 1474–1475 (2014)
40. X. Yang, M.X. Li, D.G. Deppe, G. Zhao, S. Freisem, Small oxide-free vertical-cavity surface-emitting lasers with high efficiency and high power. *Electron. Lett.* **50**(24), 1864–1866 (2014)
41. X. Yang, M.X. Li, G. Zhao, Y. Zhang, S. Freisem, D.G. Deppe, Small-sized lithographic single-mode VCSELs with high-power conversion efficiency, in *Vertical-Cavity Surface-Emitting Lasers XIV*, SPIE, ed., 7–12 Feb 2015, San Francisco, CA, USA, pp. 9381–9325

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