Design of a Short Integrated VECSEL Resonator

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In this report, the design of a short vertical extended cavity surface-emitting laser (VECSEL) is outlined. The propagation of the beam in the structure is described by a linear $ABCD$-matrix approach. The necessary radius of curvature of the output coupler is calculated. Finally, proper coupling of the emitted beam into a multimode fiber is considered.

1. Introduction

For some applications it is beneficial to integrate a vertical-cavity surface-emitting laser (VCSEL) with an external curved mirror. Here, the external mirror defines the transverse mode structure and enhances the optical field in the extended resonator.

The investigated resonator structure is schematically depicted in Fig. 1. The VCSEL consists of an active zone with a multiple quantum well structure embedded between two Bragg reflectors (DBRs). The DBRs are implemented as a thinner p-doped mirror (p-DBR) and a thicker n-doped mirror (n-DBR). A buried layer of doped AlAs above the active region is selectively oxidized. Thereby transverse optical guiding is provided. Furthermore the circular oxide aperture restricts the axial current flow to the center of the active zone. This results in sufficient transverse overlap of the laser mode and the carrier injection profile. VCSELs can be operated in a single transverse mode along with stable polarization by introducing a mode-selective loss mechanism relying on the surface grating relief technique [1].

The emission wavelength of the VCSEL is defined by the Bragg wavelength of the DBRs and by the effective length of the inner cavity. Both are adjusted for a wavelength of 850 nm. Chemical wet-etching of the p-DBR and the active zone results in a circular mesa. On top of the latter, an annular metal contact is deposited. The substrate is electrically interfaced with a planar metal contact. The VCSEL is mounted underneath a microfluidic channel, with the p-DBR facing up. The channel is fabricated from polymethyl methacrylate (PMMA). By hot embossing, a concave-shaped surface is created. This surface defines the output coupler of the laser and therefore it is coated with a dielectric DBR. Above the output coupler, an optical fiber can be plugged into a circular recess which is embossed into the PMMA. By this means, the emitted light is coupled straight into the fiber.

An aqueous solution with refractive index $n = 1.33$ perfuses the channel. The channel height is 30 µm. A 30 µm thick glass cover lid ($n = 1.51$) is bonded to the channel walls and seals the channel against leakage.

2. Resonator Model

The presented resonator structure implies a three-mirror system: two plane DBRs forming the internal resonator within the VCSEL and the curved DBR in the extended resonator. An appropriate beam analysis for such a resonator structure can be made by utilizing the ABCD-matrix law. Here a Gaussian beam is assumed. Thus the analysis is restricted to optical fields propagating close to the optical axis. This propagation as well as refraction and reflection are described by a matrix

$$M_i = \begin{pmatrix} A_i & B_i \\ C_i & D_i \end{pmatrix} . \qquad (1)$$

The index i refers to the i-th layer or interface in the structure. For simple propagation in a homogeneous layer, the elements are $A_i = 1$, $B_i = d$, $C_i = 0$, and $D_i = 1$, with d being the layer thickness. In case of a beam propagating from a medium with refractive index n_i to a medium with refractive index n_{i+1}, the elements in M_i are $A_i = 1$, $B_i = 0$, $C_i = n_i/(R_i\ n_{i+1})$, and $D_i = n_i/n_{i+1}$. The radius of curvature R_i is positive in case of a concave interface and becomes infinity in case of a flat interface. Other matrices for reflection exist, but are not included in the subsequent calculations. Hence, these calculations do not account for reflections at the parasitic interfaces, which result in a distorted laser mode. In a practical device, the air/glass interface should be anti-reflection coated in order to suppress unwanted losses from this interface.

The complex beam parameter $q(z)$ represents the real beam spot size $w(z)$ and the radius of curvature $R(z)$ of the beam front in a Gaussian beam travelling along the z-axis. The complex beam parameter is expressed by $1/q(z) = 1/R(z) - \mathrm{i}\lambda/(\pi w^2(z)\, n_i)$. Here, λ is the optical wavelength of the monochromatic beam and $\mathrm{i} = \sqrt{-1}$ is the complex unit. For every axial position, $q(z)$ can be calculated according to $q_{i+1} = (A_i + B_i\, q_i)/(C_i + D_i\, q_i)$.

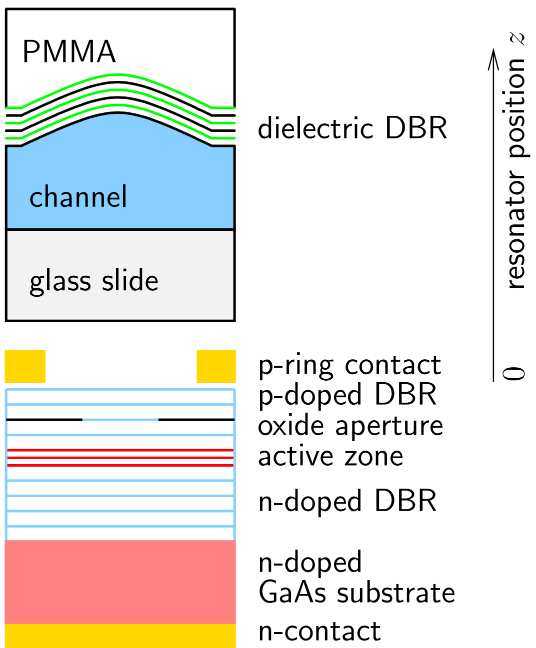

Fig. 1: Schematic drawing of the analyzed resonator structure. It comprises the VCSEL, the microfluidic channel and the hot-embossed PMMA channel wall, which is coated with a dielectric DBR.

Internal and extended resonator differ in length by more than one order of magnitude. This suggests a plane beam front passing the p-DBR, neglecting thermal lensing and other guiding or anti-guiding effects in the VCSEL [2], [3]. The radius of curvature and the beam spot size were calculated for initial beam diameters of 8 and 10 μm. The radius of curvature of the beam front is shown in Fig. 2. The invisible pole at the position $z = 0$ is in accordance with the assumed plane beam front at this point. The air/glass boundary at the axial position of 20 μm shifts the radius of curvature of the beam front towards a larger radius (i.e., weaker bending). An opposite shift is introduced at the glass/channel boundary at $z = 50$ μm. When passing the concave extended mirror at $z = 80$ μm, the radii of curvature are 158 and 264 μm, respectively. The concave extended mirror should match this curvature in order to establish a stable resonator. Doing so, the beam can make multiple bounces between the end mirrors while retaining its spot size and its radius of curvature of the beam front.

2.1 Output coupler and optical fiber launch

The aperture of the output coupler should be sufficiently larger than the beam. Any cut-off results in optical loss. The losses can be estimated from the ratio of cut-off and incident optical powers for transmission through a circular metallic aperture with radius ρ, which amounts to $\exp(-2\rho^2/w^2(z))$. The beam spot size is depicted in Fig. 3. The beam is continuously diverging from its inital diameter of 8 μm (and 10 μm, not shown here). The calculations yield loss ratios of less than $2 \cdot 10^{-6}$ for the fundamental mode in case of an aperture radius of 15 μm. Higher-order modes with a beam parameter product of $M^2 = 2$ experience a relative loss of $6 \cdot 10^{-3}$, which is substantially higher. In conjunction with a resonator loss caused by the transmitted light of approximately $2 \cdot 10^{-2}$, this facilitates mode discrimination for fundamental mode operation.

The emitted light can be coupled directly into an optical fiber. This necessitates a fiber with an aperture which is large enough to accomodate the transverse beam profile. Furthermore, the numerical aperture of the fiber should exceed that of the VECSEL. This is achieved if the beam passes the aperture of the output coupler and travels 200 μm in the PMMA. At this position, a 50 μm core diameter graded-index multimode fiber is placed. The aperture of the fiber core is expected to receive 89 % of the incident power.

3. Conclusion

The calculation of a Gaussian beam propagating in a multilayer cavity provides the necessary radii of curvature of the optical elements. By using the ABCD-matrix method the beam profile was traced along the axis of propagation. There is indication that direct optical coupling to a multimode fiber is feasible and that the resonator has favorable mode discrimination for fundamental mode operation.

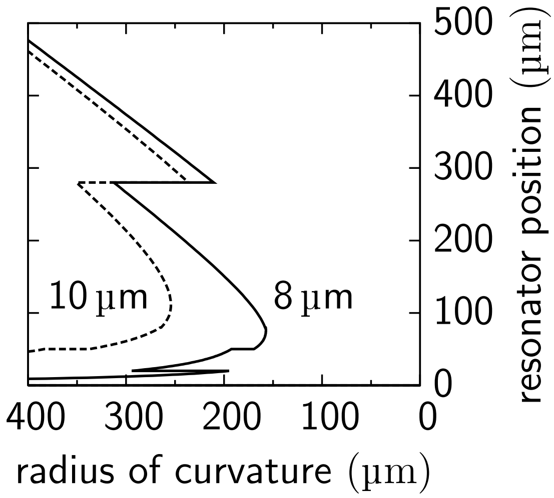

Fig. 2: Calculated radii of curvature of the beam front in the extended resonator. The beam propagates bottom up. Two different initial beam spot sizes of 8 µm and 10 µm are assumed.

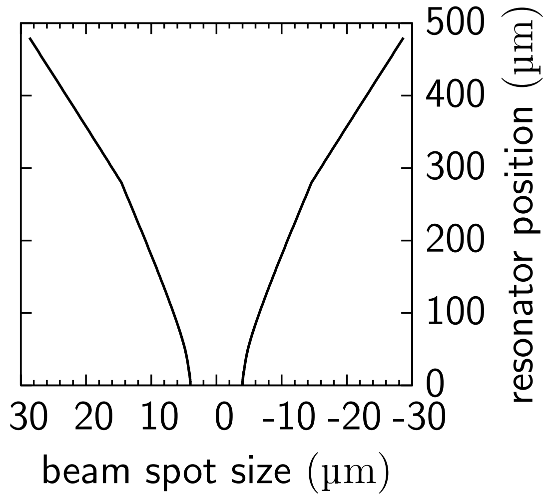

Fig. 3: Calculated beam spot sizes of the beam in the extended resonator. The direction of propagation is the same as in Fig. 2. The initial beam spot size is 8 µm.

References

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