Thermal Characterization of Electrically Injected Thin-Film InGaAsP Microdisk Lasers on Si

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***Abstract*—We have performed a numerical and experimental analysis of the thermal behavior of electrically injected microdisk lasers that are defined in an InGaAsP-based thin film bonded on top of a silicon wafer. Both the turn-on as well as the pulsed-regime temperature evolution in the lasing region was simulated using the finite-element method. The simulation results are in good agreement with experimental data, which was extracted from the broadening of the time-averaged emission spectra. Lasing at room temperature was only possible in pulsed regime due to the high thermal resistance (10 K/mW). Some strategies to decrease the thermal resistance of the microdisk lasers are proposed and discussed.**

***Index Terms*—Heterogeneous integration, InGaAsP, integrated optics, microdisk laser, Si, thermal characterization.**

I. Introduction

MICRODISK lasers have attracted much interest lately, mostly due to their potential role as very compact light sources with low power consumption in large-scale photonic integrated circuits. Several authors have reported electrically injected lasing in microdisk structures that are supported by a pedestal, with some having lasing thresholds of well below 100 μA [1]–[4]. The collection of the laser light can be done by means of evanescent coupling to a passive waveguide, as demonstrated in [5]. Our work focuses on the integration of these III–V microdisk lasers on an Si platform. This approach facilitates integration not only with silicon electronics but also with *silicon photonics*. Indeed, because of the transparency of Si at the telecommunications wavelengths 1.3 and 1.55 μm, and the fact that complementary metal–oxide–semiconductor technology can be used in the fabrication of photonic components in silicon-on-insulator (SOI) [6], silicon has emerged as a promising platform for photonic functions. A big obstacle, however, is the poor light generation efficiency of silicon. This has been addressed by using the Raman effect [7], [8]. However, the optical gain in Si remains relatively low compared with III–V materials, resulting in very long laser structures. In our approach, the integration of compact active optoelectronic components on a silicon platform is done by bonding a thin III–V film on top of it. Optically pumped lasing in microdisk lasers that are integrated on an Si wafer has already been demonstrated [9], as well as their optical coupling to an underlying SOI waveguide [10]. Another demonstration of a heterogeneous approach can be found in [11]. Recently, we have demonstrated the electrically injected lasing operation of a microdisk laser that is integrated on an Si wafer [12]. Only pulsed operation was possible at room temperature due to serious self-heating. For most practical applications, efficient continuous-wave (CW) operation at room temperature (and above) will be needed, together with a minimal thermal rollover. Therefore, this self-heating should be strongly reduced. A first step toward this goal is a thermal analysis of these integrated thin-film microdisk lasers, which is presented in this paper.

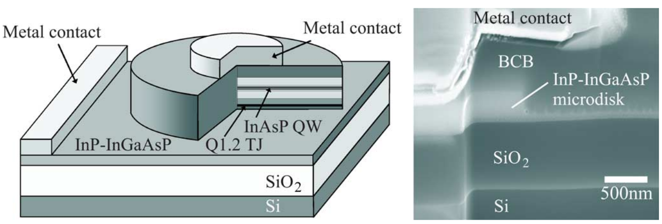

Fig. 1. (Left) Schematic representation of the microdisk laser structure and (Right) scanning-electron-microscope photo of the edge of the microdisk laser in cross section.

II. Microdisk Laser Structure and Lasing Characteristics

A schematic representation of the microdisk laser structure is given in Fig. 1. Microdisks with diameter D in the range of 4–9 μm were etched into an InGaAsP-based thin film that is molecularly bonded on top of a Si wafer, with an intermediate 1-μm-thick SiO_2 bonding layer, that is deposited with plasma-enhanced chemical vapor deposition (PECVD). The active layer contains three InAsP quantum wells that are embedded in undoped Q1.2-barrier layers and is surrounded by an n+ InP contact layer on top and a p+ InP layer below. In order to avoid high optical absorption in p-type contact layers,

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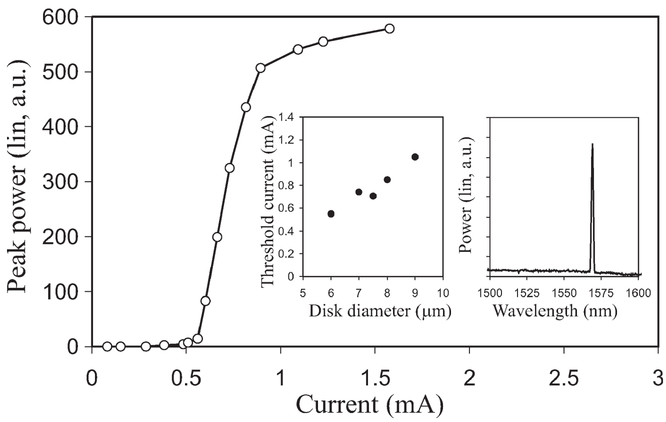

Fig. 2. Typical pulsed PI curve for $D = 6$ μm, with $T = 20$ °C (100-ns pulses, 3-μs period). Left inset: Threshold current as a function of disk diameter. Right inset: Lasing spectrum for $D = 6$ μm and $I = 0.75$ mA.

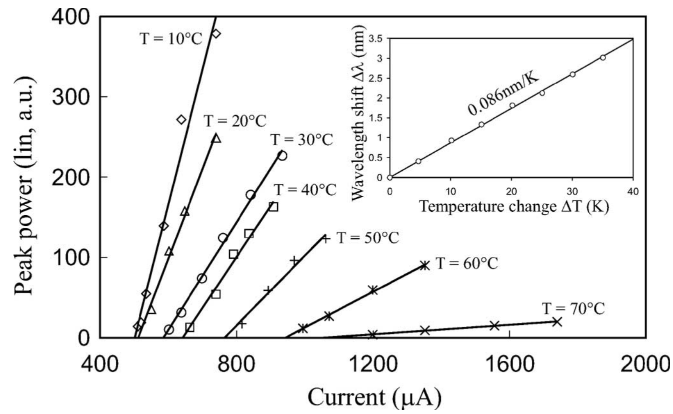

Fig. 3. Temperature dependence of the PI curve for $D = 6$ μm (100-ns pulses, 3-μs period). Inset: Temperature dependence of the lasing wavelength.

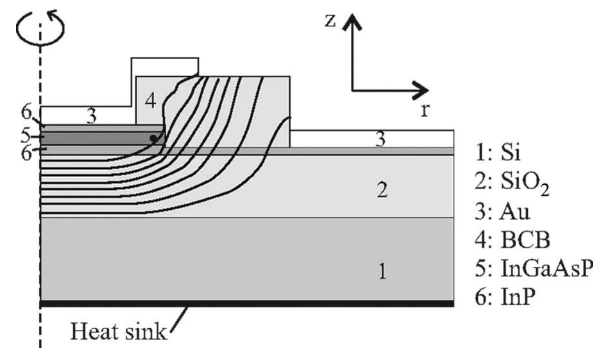

Fig. 4. Geometry used for thermal simulations, together with a typical temperature distribution. Temperatures are recorded in (black dot) the lasing region.

a reverse-biased Q1.2 tunnel junction was implemented, in combination with another n+ contact layer. The total III–V film thickness is 480 nm. The microdisk etch is incomplete, leaving an 80-nm-thick lateral contact layer at the bottom of the disk. Before depositing the metal contacts, the structure is covered with a benzocyclobutene (BCB) film, in which contact windows are etched. Since the fundamental laser modes of a microdisk are *whispering gallery* modes that are located at the edges of the disk, the top contact window is only etched open at the center of the disk to avoid excess optical absorption due to the top metal. The bottom metal contact is placed a few micrometers from the disk. A cross section of a fully processed microdisk laser is also depicted in Fig. 1. A more detailed overview of the laser structure and fabrication aspects can be found in [12]. For the electroluminescence measurements, a variable voltage was applied over the electrodes, and a fraction of the emitted light was collected by a multimode fiber and fed into a spectrum analyzer, with a minimum spectral resolution of 0.2 nm. Fig. 2 shows the peak power versus current (PI) characteristic at room temperature in the pulsed regime for a disk with $D =$ 6 μm. The PI curve reveals a clear threshold current I_{th} of 0.55 mA $(1.95\ \text{kA/cm}^2)$. The inset at the right shows the emission spectrum for $I = 0.75$ mA, with a clear laser peak at 1570 nm. The left inset shows the threshold currents for disks with D ranging from 6 to 9 μm. For $D < 6$ μm, the BCB top contact window could not be etched open. The threshold voltage varies between 5 and 7 V. This high value and its variation are due to a nonoptimal tunnel junction and nonoptimal metal contacts. Indeed, for some devices, the threshold voltage was reduced after sending a large current through the structure, most probably due to self-annealing of the metal contacts. In a second set of measurements, the temperature of the Si substrate was elevated from 10 °C up to 70 °C while recording the pulsed PI curve and the emission spectrum at each temperature. The results for $D = 6$ μm can be found in Fig. 3. Lasing was observed up to 70 °C, with $I_{\text{th}} = 1.05$ mA and a strongly reduced laser efficiency. The temperature dependence of the lasing threshold can roughly be fitted as $I_{\text{th}} = I_0 \exp(T/T_0)$, with $I_0 = 0.39$ mA and $T_0 = 71$ K. The emission wavelength λ_r shifts with temperature at a rate of $d\lambda_r/dT = 86$ pm/K. This value is lower than the expected 100 pm/K for InP-based lasers but is very close to the 90 pm/K that is reported in [3] for BCB-covered microdisk lasers. The reduction in wavelength shift is attributed to the negative temperature dependence of the refractive index of BCB. For larger disk diameters, we measured wavelength shifts of up to 95 pm/K.

III. Thermal Simulation

In order to model the thermal behavior of the microdisk lasers, the heat equation should be solved as

$$\rho c \frac{\partial T}{\partial t} = q_v + \nabla \cdot (\kappa \nabla T) \tag{1}$$

where ρ is the density, c is the specific heat, $T(\mathbf{r}, t)$ is the temperature, t is the time, q_v is the heat dissipation per unit volume, and κ is the thermal conductivity. Since the complete microdisk lasing structure has cylindrical symmetry (except for the metal pads), we chose to solve this problem in cylindrical coordinates, i.e.,

$$r \rho c \frac{\partial T}{\partial t} = q_v r + \frac{\partial}{\partial r}\left(\kappa r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\kappa r \frac{\partial T}{\partial z}\right) \tag{2}$$

with r and z being the cylindrical coordinates. Coordinate θ does not appear in the equation due to symmetry. The laser structure that was used in the thermal model is depicted in Fig. 4. The geometry parameters were taken from the cross

TABLE I
MATERIAL PARAMETERS USED IN THE THERMAL SIMULATION

Material	ρ $(\mathrm{g\,cm^{-3}})$	κ $(\mathrm{Wm^{-1}K^{-1}})$	c $(\mathrm{Jg^{-1}K^{-1}})$
Si	2.3	130	0.70
SiO_2	2.2	0.8-1.4(1.27)	0.74
Au	19.3	150	0.13
BCB	1.0	0.3	2.18
InGaAsP	4.8	6	0.31
InP	4.8	40	0.31
Al_2O_3 (c)	3.9	36	0.93
Al_2O_3 (a)	3.9	2	0.93
MgO (μc)	3.6	4	0.88

section in Fig. 1. A commercial finite-element tool was used to solve (2). Neumann boundary conditions were set on all the boundaries of the structure, except for the bottom boundary, which is kept at a fixed temperature (Dirichlet boundary condition), and thus acts as a heat sink. Convection and radiation effects can be neglected and were not taken into account. The simulated temperatures that are presented in the remainder of this paper are extracted at $r = 0.45D$ at half thickness of the III–V membrane since the thermal dependence of the lasing characteristics is determined by the temperature at the location of the laser mode (the dot in Fig. 4). The heat is assumed to be dissipated homogeneously over the entire microdisk volume, and therefore, a total dissipated power P results in $q_v = P/(\pi R^2 d)$, with R being the radius and d being the thickness of the disk. The material parameters that were used in the simulation are listed in Table I. SiO_2 films can have a thermal conductivity κ in the range of 0.8–1.4 W/mK, depending on the deposition technique [13]. Thermally grown SiO_2 films have $\kappa = 1.27$ W/mK, whereas films that are deposited by chemical vapor deposition have $\kappa \sim 1$ W/mK. For the simulations, $\kappa_{\mathrm{SiO_2}} = 1.27$ W/mK was assumed, unless specified otherwise. The thermal conductivity of Au was set to half its bulk value since the evaporated Au layer thicknesses were about 150 nm, and it is known that the thermal conductivity of Au decreases with decreasing film thickness [14]. For InP, the thermal conductivity was set to 40 W/mK, due to its high doping level.

The turn-on temperature evolution in a microdisk with $D = 6$ μm was simulated for a dissipated power of 6, 9, and 15 mW. A dissipated power of 6 mW is equivalent to a voltage of 7 V and a current of 0.85 mA (3 kA/cm^2), assuming that all power is dissipated as heat. The heat sink temperature was 15 °C. The results are shown in [Fig. 5 (black solid lines)]. From these results, thermal resistance $R_{\mathrm{th}} = 11.5$ K/mW could be extracted. The heating transient behavior can be roughly fitted by an exponential heating curve, assuming a thermal time constant of 1.67 μs. The thermal resistance was calculated for disk diameters in the range of 2–10 μm and is inversely proportional to the disk diameter: $R_{\mathrm{th}} \sim D^{-1.15}$ (see Fig. 6). The thermal resistance decreases slower with disk diameter as compared to the increase in disk area. Thus, we can expect a better thermal behavior for smaller devices, assuming that the threshold power density for lasing does not depend on disk diameter. This is due to the fact that the heat flow at the edges

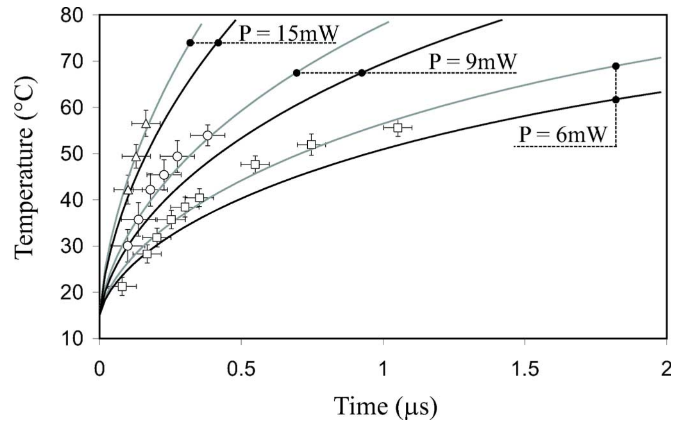

Fig. 5. Simulated turn-on temperature response for $D = 6$ μm and dissipated powers of 6, 9, and 15 mW with a heat sink temperature of 15 °C, together with the experimental results for (squares) 6 mW, (circles) 9 mW, and (triangles) 15 mW. The gray solid lines show the simulated response for $\kappa_{\mathrm{ox}} = 1$ W/mK and provide a better fit.

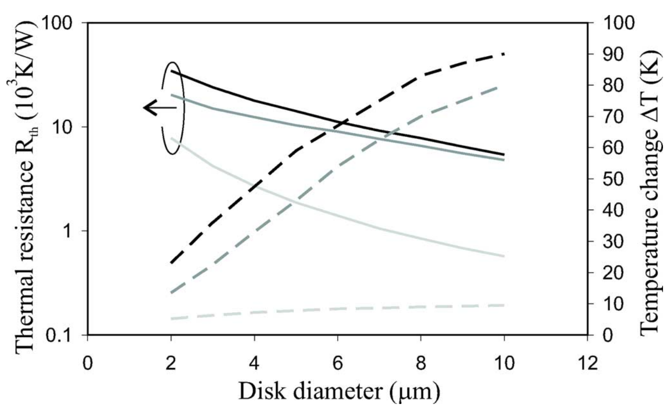

Fig. 6. (Solid lines) Thermal resistance versus disk diameter. The results for the structure in Fig. 4 are in black, the results for BCB that is replaced by amorphous Al_2O_3 are in dark gray, and the results for SiO_2 that is replaced by crystalline Al_2O_3 are in light gray. Dashed lines represent temperature increase for 21-kW/cm^2 dissipation.

of the disk becomes more dominant for smaller disk diameters. The thin lateral bottom contact layer indeed plays an important role in the heat evacuation for these smaller microdisks. To illustrate this, the expected temperature increase $\Delta T = R_{\mathrm{th}} P$ due to self-heating is plotted as a function of disk diameter, assuming a constant power dissipation of 3 kA/cm$^2 \times 7V =$ 21 kW/cm^2 (see Fig. 6). For $D = 2$ μm, ΔT is reduced to 23 K. With the heat sink at 15 °C, the device temperature should remain below 40 °C, allowing CW lasing.

The thermal resistance can be decreased by improving the heat flow through the bonding layer. Reducing the bonding-layer thickness improves heat evacuation, but bonding layers that are too thin will cause optical substrate leakage. Another option is to use a bonding material with better thermal conductivity and low refractive index, such as crystalline Al_2O_3 or microcrystalline MgO (see Table I, [15], and [16]). By replacing SiO_2 with Al_2O_3, the thermal resistance can be reduced by almost one order of magnitude [Fig. 6 (light gray lines)]. The temperature increase remains for all disk diameters under 10 K. However, bonding with (crystalline) Al_2O_3 layers is technologically far more challenging than that with SiO_2. An alternative

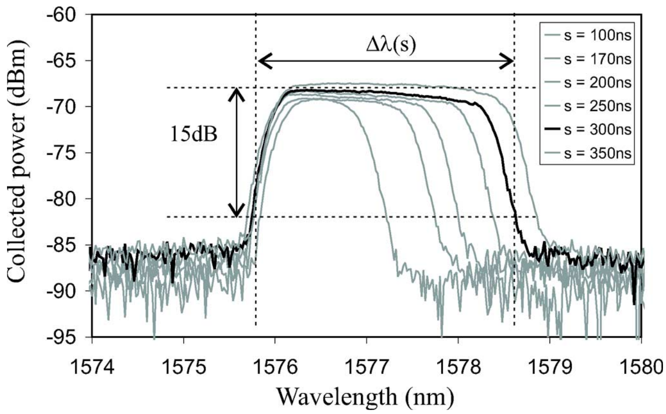

Fig. 7. Time-averaged lasing spectrum for a microdisk laser with $D = 6\ \mu$m versus pulse duration, with a fixed period of 5 μs. The spectral broadening due to self-heating is extracted at -15, -10, and -5 dB of the peak power.

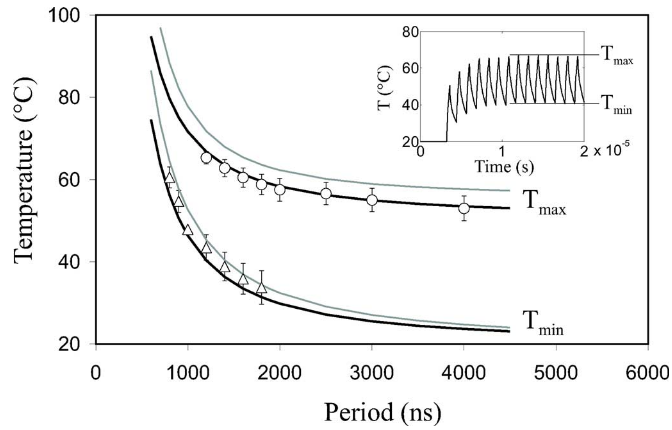

Fig. 8. Minimum and maximum pulsed-regime temperatures versus period with a fixed pulse duration (360 ns) and 11-mW dissipated power. The solid lines are the simulation results ($\kappa_{\rm ox} = 1.27$ W/mK in black and $\kappa_{\rm ox} = 1$ W/mK in gray), and the circles and triangles are the measurements. The heat sink temperature is 20 °C.

strategy is to spread the heat over a bigger area so that the heat flows through a bigger part of the bonding layer. This effect is already present due to the thin lateral InP contact layer but can be greatly enhanced if the BCB planarization layer is replaced with a better thermal conductor. It is highly unlikely that crystalline Al_2O_3 can be used as a planarization layer since it needs to be deposited; therefore, we assumed to have amorphous Al_2O_3 in this case ($\kappa = 2$ W/Km). The thermal resistance for structures where the BCB is replaced by amorphous Al_2O_3 and with a SiO_2 bonding layer is also shown in [Fig. 6 (dark gray lines)]. The thermal resistance is reduced by 10%–40%, depending on the disk diameter. However, bigger reduction might be needed to achieve CW lasing in structures with high electrical resistance, particularly, for large microdisk diameters. Finally, another solution can be used to create a thermal short circuit between the disk volume and the Si substrate by etching a hole through the bonding layer and depositing good thermal (metal) connection between the Si substrate and the microdisk.

IV. Experimental Thermal Characterization

In order to test our simulation results, we extracted the heating and cooling behavior of the microdisk lasers by inspecting the laser emission spectrum as a function of pulse drive parameters. As the microdisk temperature increases due to self-heating, the emission wavelength shifts to longer wavelengths at a rate $d\lambda_r/dT$. This effect is visible on the recorded spectra as a broadening of the laser peak since the spectrum analyzer integrates the collected optical power over a time period that is much longer than the thermal time constant.

In the first set of measurements, the pulse period was set to a fixed value (5 μs), which is long enough to allow the device to cool down between current pulses. Then, the emission spectrum was measured as function of pulse duration s. The spectra for a device with $D = 6\ \mu$m are shown in Fig. 7. The left edge of the laser peak can be found at approximately the same wavelength for all pulse durations. The right edges, however, show an increasing red shift with increasing pulse duration. For each spectrum, the spectral broadening $\Delta\lambda(s)$ was measured at -15, -10, and -5 dB from the peak power. For each of these measurement sets, maximum temperature $T(s)$ at the disk edge was then estimated using

$$T(s) = T_{\rm hs} + \frac{\Delta\lambda(s) - \Delta\lambda_0}{d\lambda_r/dT} \qquad (3)$$

where $T_{\rm hs}$ is the heat sink temperature, $d\lambda_r/dT = 86$ pm/K, and $\Delta\lambda_0$ is the spectral broadening due to the limited resolution of our measurement setup, which depends on the power level at which the linewidth is extracted. For a resolution of 0.2 nm, we get $\Delta\lambda_0 = 1.11$ nm at -15 dB, assuming a Lorentzian line shape. These experimental results are compared with the simulated thermal turn-on response in Fig. 5 for $D = 6\ \mu$m and dissipated powers of 6, 9, and 15 mW. The horizontal error bars show the uncertainty on the pulsewidths due to electrical loading effects, whereas the vertical error bars show the variation on the measurement that results from extracting the spectral broadening at different power levels. The experimental results show a slightly higher device temperature than the simulations with $\kappa_{\rm SiO_2} = 1.27$ W/mK predict. Decreasing $\kappa_{\rm SiO_2}$ to 1 W/mK gives a better fit.

In the second set of measurements, the pulse duration was fixed at 360 ns, and the period was varied. For shorter periods, the device does not get the time to cool down to the heat sink temperature, and heat gradually accumulates at each period. In the regime, the temperature will oscillate between minimum temperature $T_{\rm min}$ and maximum temperature $T_{\rm max}$, which are both dependent on the period. Thus, this measurement also incorporates the cooling behavior of the device. The results for a device with $D = 7\ \mu$m, $P = 11$ mW, and $T_{\rm hs} = 20$ °C are shown in Fig. 8. For $T > 65$ °C, the lasing signal was too weak to do proper spectral inspection. For $T < 30$ °C, there was mode competition with a higher order mode (at shorter wavelength), which prevented a straightforward extraction of the minimum regime temperature. In this case, experimental results agree slightly better with $\kappa_{\rm SiO_2} = 1.27$ W/mK than with $\kappa_{\rm SiO_2} = 1$ W/mK. Based on these two experiments, we conclude that the SiO_2 film has a thermal conductance in the range of 1–1.27 W/mK, which is consistent with its PECVD-nature.

V. Conclusion

We have performed a numerical and experimental analysis of the thermal behavior of electrically injected microdisk lasers that are defined in an InGaAsP-based thin film bonded on top of a silicon wafer, incorporating a BCB isolation and planarization layer. Lasing at room temperature was only possible in pulsed regime due to self-heating effects. Simulation results indicated that the thermal resistance is on the order of 10^4 K/W. The thermal behavior can be improved by using a material with a higher thermal conductivity, such as Al_2O_3, for the bonding layer and/or the isolation layer. The thermal turn-on response and pulsed-regime temperatures were experimentally extracted by inspecting thermal spectral broadening, and the results were found to be in good agreement with simulation results.

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Prof. Baets is a member of the Optical Society of America, the IEEE Lasers and Electro-Optics Society (LEOS), The International Society for Optical Engineers, and the Flemish Engineers Association. He has been a member of the program committees of a.o. OFC, ECOC, the IEEE Semiconductor Laser Conference, ESSDERC, CLEO-Europe, the LEOS Annual Meeting, Photonics Europe, and ECIO. He was the Chairman of the IEEE-LEOS-Benelux Chapter from 1999 to 2001. From 2003 to 2005, he was an elected Member of the Board of Governors of the IEEE LEOS.