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Enhanced side-mode suppression in chaotic stadium microcavity lasers

S. N. M. Mestanza,[1,a)] A. A. Von Zuben,[3] and N. C. Frateschi[2,3]
[1]Federal University of ABC, CEP 09210-170, Santo André, São Paulo, Brazil
[2]Center for Semiconductor Components, P.O. Box 6061, University of Campinas-UNICAMP, 13083-870, Campinas, São Paulo, Brazil
[3]"Gleb-Wataghin" Physics Institute, P.O. Box 6165, University of Campinas-UNICAMP, 13083-970 Campinas, São Paulo, Brazil

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We report an enhanced side-mode suppression in Bunimovich stadium lasers with strained InGaAs/InGaP quantum well (QW) active regions. This is realized with spatially selective carrier injection along a particular periodic orbit of the stadium. The selectivity is achieved using He^{+3} ion implantation. Up to 21 dB enhancement in side-mode suppression is observed for a $40\times 20\ \mu m^2$ stadium with interband transition between the first excited quantum well level. The improvement in side-mode suppression is apparently a consequence of coherent beating between orbits leading to a Vernier effect. A simple model corroborate with this hypothesis. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3082479]

Microcavity lasers based on whispering gallery modes have long been proposed and exhaustively investigated.[1–3] These devices can have high quality factor (Q). However, the lack of light directionality, poor spectral control, and small external differential quantum efficiency has attracted the use of alternative geometries with boundaries based on chaotic billiards,[4] particularly the Bunimovich stadium.[5]

It has been shown by Heller that the eigenmodes of the Helmholtz equation in the semiclassical limit for the stationary solution of the Schrödinger equation in Bunimovich stadium wells have higher amplitude along classical periodic orbits, called scars.[6] Bogomolny[7] also showed that averaged wave-functions for very high quantum numbers lead to scars, which he completely mapped for this geometry. Analogously, the same behavior is expected for the resonance modes of optical cavities with dimensions reasonably larger than the wavelength of light.

In literature, several works investigated the light directionality in a great variety of resonance cavity sizes and geometries. Backers and co-workers[8,9] showed an increase in light directionality for elliptical optical cavities and for disks with scattering structures. Nockel and co-workers[10,11] proposed the use of optical cavities with boundaries based on chaotic billiards, particularly stadium. An increase in light directionality is achieved for devices with small eccentricity and dimensions much larger than the wavelength of light.

In this work we present the fabrication of InGaAs/GaAs/InGaP Bunimovich stadium lasers with spatially selective carrier injection along a diamond orbit or scar. Side-mode suppression (SMS) enhancement is observed for these structures. A simple model predicts the coexistence of the diamond and the bow-tie scars. The Vernier[12] effect of the beating between these scars in conjunction with the limited gain bandwidth is apparently causing the SMS.

The epitaxial structure of our devices is as follows: n^+-GaAs substrate and buffer; n-InGaP ($1.05\ \mu m$, $1\times 10^{18}\ cm^{-3}$); n-InGaP ($0.15\ \mu m$, $5\times 10^{17}\ cm^{-3}$); undoped GaAs ($0.10\ \mu m$); undoped $In_{0.21}Ga_{0.79}As$ quantum well (8 nm) for an emission at $\lambda \sim 0.98\ \mu m$ and $\lambda \sim 0.90\ \mu m$ at 300 °K for transitions between the first and second quantum well levels, respectively; undoped GaAs ($0.10\ \mu m$); p-InGaP ($0.10\ \mu m$, $2\times 10^{17}\ cm^{-3}$); p-GaAs etch-stop layer (6 nm, $2\times 10^{17}\ cm^{-3}$); p-InGaP (50 nm, $2\times 10^{17}\ cm^{-3}$); p-InGaP ($0.91\ \mu m$, $6\times 10^{17}\ cm^{-3}$); p-InGaP ($0.19\ \mu m$, $1\times 10^{18}\ cm^{-3}$); p^+-GaAs ($0.1\ \mu m$, $3\times 10^{19}\ cm^{-3}$) and contact p^{++}-GaAs layer ($0.1\ \mu m$, $>5\times 10^{19}\ cm^{-3}$). Uniform and spatially selective carrier injection devices were fabricated side by side. Processing for the uniformly pumped devices is described below: p-side Ti/Pt/Au metallization. Subsequently, the entire structure is reactive ion etching (RIE) dry etched by $SiCl_4$/Ar plasma.[13] Finally, the n-side is metallized with Au/Ge–Ni–Au. Bunimovich stadium (two semicircles with radius R united by a square of side $2R$) were fabricated. The devices with spatially selective injection were fabricated as follows. First, $1.5\ \mu m$ thick photoresist layer protects a region along a diamond scar. Subsequently, He^{+3} implantation is performed to isolate the unprotected regions.[14] Choice of He^{+3} ion energy and dose was based on calculations of radiation defect distributions by transport of ions in matter Monte Carlo simulation. For 100 keV He^{+3} the radiation damage formation occurs only within almost the entire InGaP layer. 15° incidence angle was used to avoid channeling effects. Sheet resistance in excess of megaohm is obtained after a dose of $\sim 10^{13}\ cm^{-2}$. Subsequently, the laser stadium structures with and without scars of radius $R=10$, 15, and $20\ \mu m$ were fabricated. The inset in Fig. 1(b) shows a scanning electron microscope micrograph of the devices with and without implantation.

Figure 1(a) shows the normalized angular dependence of the emission for a stadium without scar with a $20\ \mu m$ radius, operating with a current of 60 mA. All measurements were done at 10 °C in pulsed mode ($1\ \mu s$, 1% duty cycle). The angular dependence was measured using an optical fiber moving transversally to the emission direction. The emission at two orthogonal directions was measured. We observed ten

a)Author to whom correspondence should be addressed. Electronic mail: nilo@ufabc.edu.br.

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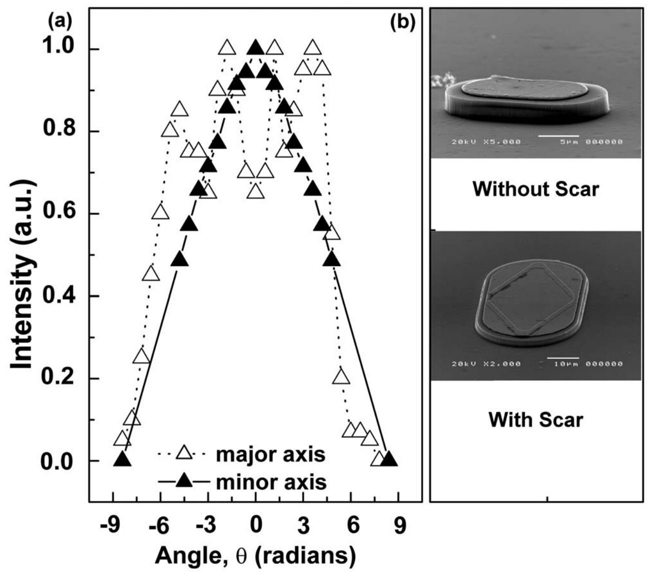

FIG. 1. Normalized angular dependence of the emission for a stadium without scar ($R=20$ μm and driving current 20% above threshold). (▲) Along the major axis and (△) along the minor axis.

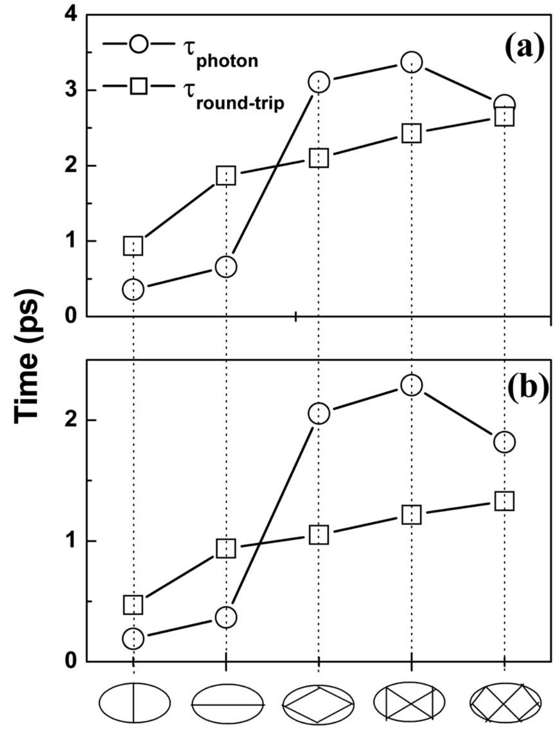

FIG. 2. Calculated photon lifetime and round trip time for five scars with the highest probability to exist in our structures. (a) $R=20$ μm; (b) $R=10$ μm.

times higher power with a single lobe for the emission along the stadium major axis, shown in closed triangles. Along the minor axis, shown in open triangles, multiple lobes are observed. Unlike previous reports, we cannot find a single scar that agrees with this angular pattern. We assume that a superposition of scars is occurring. In order to find the components of this superposition in agreement with the scars foreseen by Bogomolny, we have made the following considerations: (a) We considered only symmetrical periodic scars, (b) we ranked the scars from smallest to largest round trip times, (c) we ranked the scars from smallest to largest number of reflection points, and (d) we neglected two modes with orbits too close to the borders. With this simple procedure, we find five scars that would fit the observed angular pattern: *Fabry–Perot*, in the direction of major and minor axis, respectively, diamond, bow tie, and double diamond.

Assuming that these scars are present in the structure, it is interesting to calculate the photonic lifetime ($\tau_{\mathrm{photon}}=Q/\omega_p$) for each one of them and compare to the round trip time ($\tau_{\mathrm{round\ trip}}=l\eta/c$). Here, l is the length of the orbit, η is the index of refraction, ω_p is the pth resonance frequency, and c is speed the light. The larger the excess of the photonic time compared to the round trip time, the higher the possibility that scar can survive and lead to stimulated emission. In order to calculate Q, we developed a model based on a simple approach where the field amplitude is given by $E=E_o\exp[i(k+i\alpha_o/2)l-\omega t]$. Here, α_o is the optical scattering loss and k is the wave number in the material $\eta\omega/c$. We assume an amplitude reflectivity of r. Considering a summation over infinite round trips, we find the frequency dependent field intensity $I(\omega)$ and expand it near a resonance ω_p to obtain a Lorentzian line shape. We obtain the energy exponential $I(t)$ decay with a Fourier transform of $I(\omega)$. With $I(t)$, Q is found to be $Q=\omega_p l\eta/(2c\sinh[q\ell n(r)/2-\alpha_o l/4])$, where q is the number of reflection points for a given scar.

In order to obtain realistic r and α_o values, we fabricated broad-area lasers with RIE etched mirrors with the same epitaxial material and the same process as for the stadium resonator. We obtained $\alpha_o=32$ cm^{-1} and $r^2=13\%$ from the threshold current density and external quantum efficiency dependence with the cavity length. Since a cleaved facet provides $r^2=30\%$, we estimated that scattering loss are about 17%. Considering the diamond and the bow-tie scars of our structures, we expect total internal reflection. With the scattering loss, we then estimated $r^2=83\%$ in our calculation. Figure 2 shows the calculated τ_{photon} and τ_{round} for the five scars mentioned above for two Bunimovich stadiums with radii (a) 10 μm and (b) 20 μm. Clearly, the diamond and the bow-tie scars are the only candidates for lasing. Also, the double diamond may be present, but is less probable. The larger structures have a larger excess in τ_{photon} lifetime, and therefore, should require less gain for lasing.

The emission spectra for stadium with different radii and a current injection 20% above threshold were investigated. Figure 3(a) shows the spectra for the devices without implantation. As expected, multimode behavior is observed in all cases. We also observe that the emission of the 20 μm stadium corresponds to the first QW level transition $\lambda\sim980$ nm, while the smaller stadium shows lasing for transitions between the first excited QW level, $\lambda\sim890$ nm. For comparison, Fig. 3(b) shows the spectra obtained for the corresponding neighbor devices with ion implantation forcing the injection along the diamond scar. Great enhancement in SMS is observed. Also, it is clear that the suppression is further augmented for smaller structures. Figure 4 shows the SMS for the different structures with and without selective

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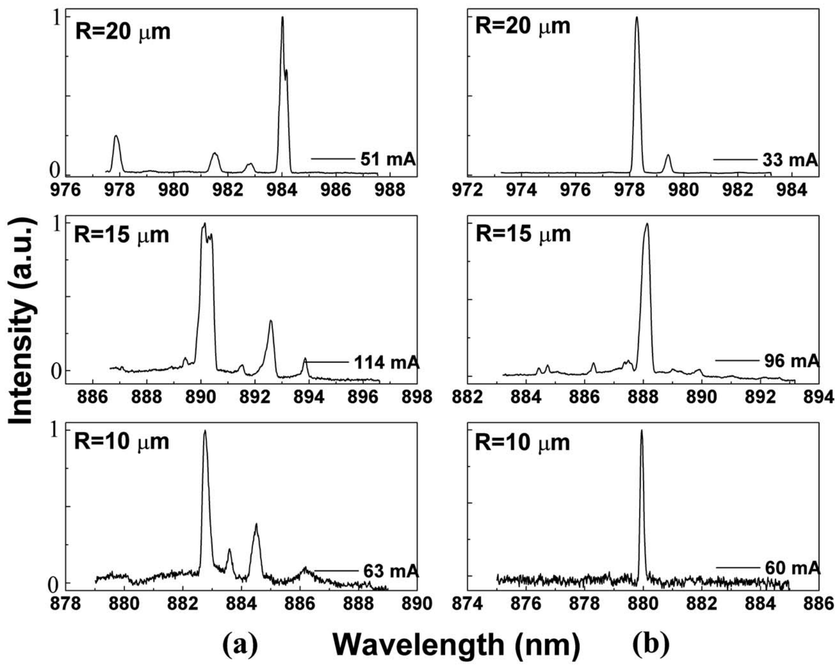

FIG. 3. Normalized spectra 20% above threshold for stadium with R =10, 15, and 20 μm: (a) without scar injection and (b) with scar injection.

carrier injection. SMS enhancement of 3, 6, and 21 dB are observed for devices with 20, 15, and 10 μm, respectively.

We believe that with uniform pumping the two scars act as two incoherent resonant cavities. However, when we force injection over one of the scars, the second scar is excited coherently by it. Therefore, coherent beating can occur. With the beating, the Vernier effect can take place and common modes to both scars are more separated in energy than the individual modes of each scar separately. Given a fixed gain bandwidth, this energy separation leads to SMS. In the case of lasing at the first excited mode of the quantum well, the gain bandwidth is narrower leading to yet more SMS. We also expect that if there is mode coupling, the true wave pattern may be a hybrid of the two scars, and this could manifest itself in an emission pattern that is distinct from either the pure diamond or pure bowtie. However, the measured emission is affected by the Q of the modes. Higher Q modes concentrate more energy within the resonator. Therefore, spontaneous emission may be less detected. On the other hand, stimulated emission should be dominant for the higher Q modes. Therefore, it is difficult to predict the resultant emission pattern.

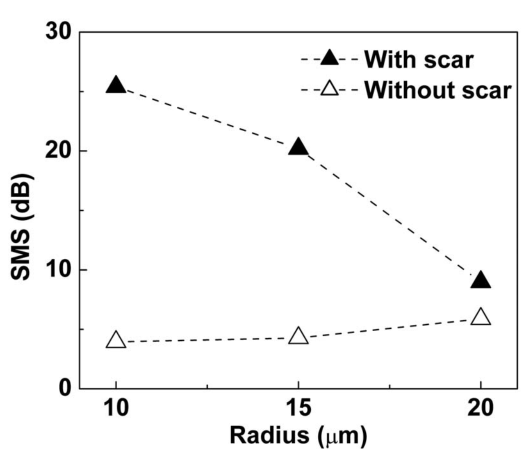

FIG. 4. SMS as a function of the stadium size: (▲) with selective current injection and (△) without selective current injection.

In conclusion, Bunimovich stadium lasers with spatially selective carrier injection along a diamond scar were fabricated. Selective injection was achieved with He^3 implantation. SMS enhancement of about 21 dB was obtained for 20×10 μm^2 devices operating at the first excited quantum well mode. The improvement in SMS is apparently a consequence of the Vernier effect and the fixed gain bandwidth.

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