May 15, 2015 / Vol. 40, No. 10, p. 2261 / OPTICS LETTERS

Long-range surface plasmon amplification with current injection on a one-dimensional photonic crystal surface

Valery Konopsky[1]

[1] *Institute of Spectroscopy, Fizicheskaya, 5, Troitsk, Moscow, 142190, Russia (konopsky@gmail.com)*

compiled: May 5, 2015

A one-dimensional (1D) semiconductor photonic crystal (PC) structure with a terminal metal nanofilm, supporting propagation of long-range surface plasmons (LRSPs), is considered as an LRSP amplifier with current pumping. Current is injected to an active region through the metal nanofilm from one side and doped semiconductor layers from the other side. The propagation length of LRSP waves in such 1D PC structures reaches several millimeters, and therefore, a gain as low as $10\,\mathrm{cm}^{-1}$ is enough to compensate for attenuation and amplify LRSPs. A unique advantage of this structure is that the refractive index of LRSP wave is very close to unity. As a result, no return reflection to semiconductor occurs during the edge-emission of LRSP to air, and this enhances the light extraction efficiency from semiconductor light sources such as edge-emitting superluminescent diodes and light-emitting diodes (LEDs). Optical feedback may be incorporated in this LRSP amplifier by grating deposition on the external side of the metal nanofilm and LRSP lasing (i.e., long-range SPASER) may be realized without the use of complicated "etch-and-regrow" processes.

OCIS codes: (250.5403) Plasmonics; (230.5298) Photonic crystals; (240.6690) Surface waves; (140.3490) Lasers, distributed-feedback; (230.3670) Light-emitting diodes.

http://dx.doi.org/10.1364/OL.40.002261

The high refractive index (RI) of semiconductor materials results in low light extraction efficiency from semiconductor light sources. The large RI difference between air and semiconductors makes the reflection quite substantial on a planar semiconductor/air interface even at normal incidence of light (Fresnel loss). Total internal reflection of light, which occurs at incident angles as low as 17° at this interface (for an RI of approximately 3.5 for a semiconductor), also leads to trapping of the light within the semiconductor structure (critical angle loss).

The light generation inside the planar semiconductor structure usually occurs in a thin active layer, such as a nanometer-thick quantum well (QW), and further light amplification occurs during its propagation along a waveguide surrounding the QW. Effective refractive index of such ordinary waveguide cannot be less than the RI of the waveguide cladding. Therefore, the generated light gets partially reflected back to the semiconductor during edge emission. For superluminescent diodes and semiconductor optical amplifiers, such edge reflection is an inappropriate feature that inhibits the increase of their power because of an undesirable lasing.

In our work [1] we have shown that in the structure of a "metal nanofilm on 1D PC", ultra-long-range propagation of surface plasmon (SP) waves is possible with an effective refractive index ρ, which is very close to the RI of the external media (e.g., air, $n_e \simeq 1.0003$). Furthermore, the propagation length of these ultra-LRSP waves in 1D PC reaches several millimeters and exceeds that of ordinary SPs by two orders of magnitude. In this Letter, we describe a conception and discuss design principles of light sources with current injection based on these ultra-LRSPs in 1D PC semiconductor structures.

SPs, which are transverse magnetic (TM) optical surface waves propagated along a metal-dielectric interface [2], have applications in various fields. In the field of semiconductor light sources, several attempts have been made to utilize SPs for improving emission characteristics of the light sources. In the works of Köck *et al.* [3–5] it was shown that the SP coupling mechanism has the potential to increase external quantum efficiency of conventional AlGaAs/GaAs double-heterostructure LEDs and of Ag/n-GaAs Schottky diodes.

In 2003, the concept of nanolaser based on surface plasmon amplification by stimulated emission of radiation (SPASER) was proposed by Bergman and Stockman [6]. SPASER with optical pumping has been experimentally realized in 2009 [7], but an electrically pumped SPASER has not been demonstrated yet.

The main limiting factor for electrically pumped SPASER (and for all SP applications) is a strong intrinsic damping of SP field in a metal. When SP is confined in a very small modal volume in all dimensions, the SP damping increases considerably because the major section of the SP field is localized in a metal nanostructure. This is the so-called "confinement-attenuation trade-off": the more confined the SP, the greater is its attenuation. Such trade-off between high confinement, and low loss of SPs makes the realization of subwavelength-sized, electrically pumped SPASER hardly achievable [8] because threshold current density becomes too high.

One way to decrease the SP attenuation and increase the SP propagation length is to use long-range SPs, which can be achieved using a thin metal film embedded between two dielectrics with identical RIs [9, 10]. Such LRSPs in metal nanofilms are at the other end of the trade-off, having a low attenuation and large propagation length for the price of low confinement because most of the SP energy propagates beyond the metal nanofilm. Therefore, LRSP is not confined to very small modal dimensions, but it does propagate with lower loss, which reduces the material gain required to achieve LRSP amplification [11].

Several experimental studies involving LRSP amplification and lasing have been reported (for review see [12]). For example, an optically pumped SPASER capable of generating 25 mW of external peak power from SP-radiation conversion was obtained by sandwiching a gold-film plasmonic waveguide between identical InGaAs quantum-well gain media [13]. The authors obtained an internal loss of $720\,\mathrm{cm}^{-1}$, which is much higher than the theoretical ohmic loss of $45\,\mathrm{cm}^{-1}$ for LRSP in their configuration; they assume that this loss increase is attributed to the difficulties in the flip-chip bonding of two identical dies because of voids and other defects in the Au film at the interface between two dies. Further, note that in such a symmetrical design, the effective RI of LRSP is approximately equal to the high RI of a semiconductor cladding, which leads to Fresnel loss. Next, we present the design of electrically pumped asymmetrical structures supporting ultra-long-range SP propagation with an effective RI close to the RI of air, thereby completely avoiding Fresnel loss.

As was shown in [1], the requirement that the RIs of two dielectrics must be similar, which is required for LRSP excitation in the symmetrical structure *"dielectric/metal/dielectric"* may be circumvented by using the asymmetrical structure *"1D PC/metal/dielectric"*. The 1D PC is a simple periodic multilayer stack. Transverse electric (TE) optical surface waves (SWs) in 1D PCs were studied both theoretically [14] and experimentally [15] in the 1970s. In recent years, the PC SWs (with TM and TE polarization) have been used in important applications such as gas sensors [16] and optical biosensors [17].

The confinement of optical field (for the PC SWs in question) is the result of a photonic band gap from one side and total internal reflection (TIR) from another side of an interface. Note that PC SWs, which do not use TIR, fall into another category of so-called "optical Tamm states", where the confinement of optical field near an interface between a 1D PC and a semi-infinite metal (or a metal film with a thickness larger than the penetration depth in the metal) is achieved as a result of the photonic band gap from one side and negative dielectric constant of the metal from another side [18]. A strong intrinsic damping in the metal is unavoidable for the "optical Tamm states", while for the PC SWs in the presented structure it is considerably reduced.

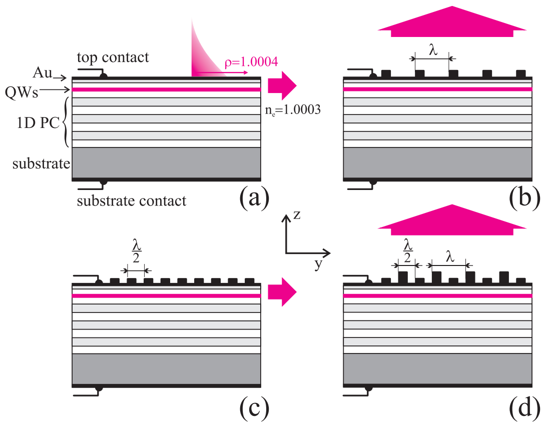

Fig. 1. Schematics of the LRSP-based superluminescence LEDs: (a) edge-emitting and (b) surface-emitting and schematics of the LRSP-based laser diodes: (c) edge-emitting and (d) surface-emitting.

In what follows we present a calculated *"1D PC/metal nanofilm/air"* structure that supports propagation of TM-polarized SWs, where 1D PC is a semiconductor heterostructure with an active region (three QWs) in the last but one semiconductor layer. A schematic of the proposed structure is shown in Fig. 1(a). For the design of this structure, we will use our algorithm described in [19]. Using this algorithm, we calculate the parameters for the structure and show that the ultra-LRSP propagation can be excited in the terminal metal layer, bordering with air (RI $n_e \simeq 1$).

Type	Composition	Width	RI
	air	∞	1.0003
metal	Au	11 nm	0.16+i·3.82
barrier	n$^+$-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$	12 nm	3.2+i·0.01
$QW_{tensile}$	i-$Ga_{0.8}In_{0.2}As_{0.3}P_{0.7}$	9 nm	
barrier	i-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$	24 nm	3.2
QW_{compr}	i-$Ga_{0.2}In_{0.8}As_{0.95}P_{0.05}$	6 nm	
barrier	i-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$	38 nm	3.2
$QW_{tensile}$	i-$Ga_{0.8}In_{0.2}As_{0.3}P_{0.7}$	9 nm	
barrier	i-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$	12 nm	3.2
1D PC	p-$Ga_{0.51}In_{0.49}P$ (N)	52.9 nm	3.45+i·0.001
	p-$Al_{0.51}In_{0.49}P$	57.6 nm	3.03+i·0.001
($N > 16$)	. . . *(repeated N times)*	. . .	. . .
substrate	p-doped GaAs	∞	3.75+i·0.15

Table 1. Parameters of PC-based structure supporting ultra-LRSP propagation and emission at $\lambda \simeq 690\,\mathrm{nm}$.

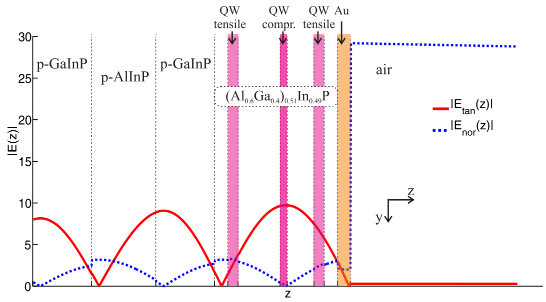

Fig. 2. Distribution of the LRSP field components in the final layers of the PC bordering with air.

To engineer such LRSP-based light-emitted devices, we exploit an active region with TM-polarized light emission, whereas most semiconductor lasers and LEDs emit light with TE polarization. When a QW is used as the active region, a sign of strain in the QW has strong influence on the polarization of emitted light. The effects of quantum confinement and the compressive strain of the QW give rise to TE main emission. Tensile strain, strong enough to overcome the effect of quantum confinement, results in dominant TM-polarized spontaneous emission and optical gain [20]. We design a PC-based structure for emission at $\lambda \simeq 690\,\mathrm{nm}$, composed of alternating layers of AlInP/GaInP with appropriate QWs in the last but one semiconductor layer. The designed structure has the *substrate/1D PC/QWs/M/air* layout, whose parameters are presented in Table 1. All layers of the structure (excluding QWs) are lattice matched to GaAs substrate. To provide an ohmic contact with the metal nanofilm, the last semiconductor layer is heavily doped or contains a delta-doped sublayer. The type of doping (n- or p-) for the last semiconductor layer should be chosen taking into account properties of a particular semiconductor/metal interface to minimize resistance of the ohmic contact at this interface. For design presented in Table 1, we have chosen the n^+-doped semiconductor layer in ohmic contact with the metal nanofilm, and, correspondingly, the p-doped semiconductor multilayer from another side of the undoped active layer. Then, as usual, a forward bias for the p-n heterojunction should be applied for current pumping of the active layer.

Spatial field distribution of the LRSP wave in several final layers of the structure is depicted in Fig. 2. It can be seen that the LRSP field within the 1D PC has both normal and tangential components with a phase difference of $\pi/2$, whereas, outside the structure, the normal component of the field is dominant. Both phase-shifted components, normal (E_z) and tangential (E_y), lie in the plane of the figure (TM polarization). This fact permits us to use both types of QWs: two tensile strained $\mathrm{QW}_{\mathrm{tensile}}$ and one compressive strained $\mathrm{QW}_{\mathrm{compr}}$, located near the corresponding maxima of normal and tangential components of the field in the undoped region of the structure. Note that, here, $\mathrm{QW}_{\mathrm{compr}}$ is used to generate the tangential field with a polarization vector that lies along the direction of the wave propagation (i.e., it is not TE polarization with a polarization vector that is perpendicular to the direction of the wave).

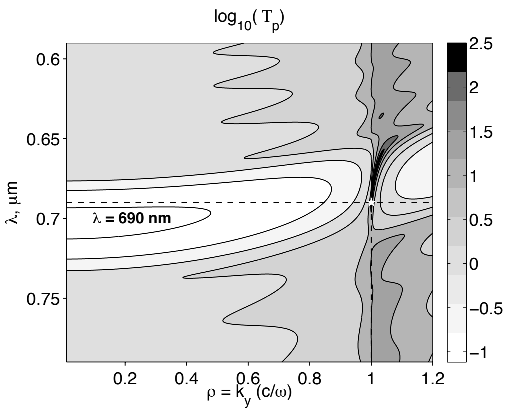

Fig. 3. Dispersion of the 1D PC structure with the terminal gold nanolayer in air. A point where ultra-LRSP propagation occurs is designated as a white pentagram at the intersection of the lines representing $\lambda = 690\,\mathrm{nm}$ and $\rho = 1.0004$. The LRSP mode is seen as a dark curve (with an enhancement much more than 10^2), which is located within the band gap (in whitish areas with an enhancement less than 1).

Compositions and thicknesses of $\mathrm{QW}_{\mathrm{tensile}}$ and $\mathrm{QW}_{\mathrm{compr}}$ shown in Table 1 are taken from [21]. The additional advantage of the PC-based structure is the possibility to use wide band gap semiconductors in the undoped barrier region and, therefore, increase the QW depth by this means. Despite of a low RI of the wide band gap semiconductors, they will support waveguide propagation in this undoped region in contrast to ordinary waveguides where a high RI core is required.

In Fig. 3 a dispersion of the designed structure is shown as the logarithm of the optical field enhancement (i.e., as $\log T_p$, where T_p is multilayer transmission) in the external medium near the structure. The photonic band gap is clearly seen as the whitish areas with an enhancement much less than 1. The dispersion is presented using the coordinate $\lambda(\rho)$. The angular parameter $\rho = n\sin(\theta)$, at which the excitation of the surface mode occurs, is equal to the effective RI of the mode.

The propagation length of the ultra-LRSP mode, which can be estimated from the resonance width of the mode, is more than one millimeter. This is approximately two orders of magnitude higher than the propagation length of ordinary SPs at the same wavelength. Such low theoretical ohmic loss (about $10\,\mathrm{cm}^{-1}$ for the structure with parameters shown in Table 1) implies the potential for realizing devices with high differential gain and low laser threshold.

From this dispersion figure, it can be seen that field enhancement at the wavelength of spontaneous emission from QWs ($\lambda \simeq 690\,\mathrm{nm}$) occurs only at $\rho \simeq 1$, whereas at other values of ρ in this wavelength a field suppression occurs. Therefore a good Purcell enhancement of spontaneous emission into LRSP mode can be expected because photonic density of states is high only on the LRSP curve and very low everywhere else within the photonic band gap.

In [1, 19], we have revealed that the effective RI of LRSPs ρ should be close to the external medium RI n_e:

$$\rho_\alpha = n_e + 2\alpha^2 \frac{{n_e}^3 {d_m}^2 \pi^2}{\lambda^2}\,, \tag{1}$$

where α is in the range $[0\ldots 1]$.

The standard LRSP, excited in symmetric configuration (a thin metal film with thickness d_m embedded between two identical dielectrics), has an effective RI of $\rho_{1/2}$ (where $\alpha = 1/2$) and wavevector $k \simeq \frac{\omega}{c}\rho_{1/2}$ [22]. In this case, the minimum of the EM field of LRSP is always located at the center of the metal film.

In addition, it was stated in [1, 19] that the LRSPs become ultra-long-range SPs if they have an effective RI of ρ_0 (i.e., ρ_α with $\alpha \to 0$) and the minimum of the EM field in this case is located near an external border of the metal nanofilm. This condition can be fulfilled when a thin metal film is deposited on a 1D PC with an appropriate structure. The excitation of the ultra-LRSP in such an asymmetrical structure can be accomplished by wavelength tuning to an optimal value of α near zero. In active devices, such as superluminescence diodes and lasers (with wide enough gain spectrum), this condition ($\rho \to \rho_0$) will be fulfilled automatically at an appropriate wavelength within the gain spectrum, and the ultra-long-range propagation will occur at this wavelength.

One of the unique properties of the proposed structure is the possibility to deposit gratings on the external side of the metal nanofilm after the completion of epitaxial growth, thereby completely avoiding the use of complicated "etch-and-regrow" processes. The LRSP field reaches its maximum at the external surface of the metal nanofilm, and interaction between the grating and the propagated LRSP wave will be strong. This permits the vertical emission of radiation through the surface of the LED or laser, as shown in Fig. 1(b) and (d), respectively, by depositing the grating with the λ-component in its Fourier spectrum. Another important possibility in using gratings on the metal nanofilm surface is the incorporation of distributed feedback into the proposed LRSP amplifier. As shown in Fig. 1(c), a grating with the period $\lambda/2$ may be used for this purpose because the LRSP wavelength differs little from free-space wavelength. This should lead to the realization of the SP oscillator, which may be named as LRSP laser or long-range SPASER.

The presented approach can also be implemented in any other spectral range where semiconductor sources of TM-polarized spontaneous emission are available; for example, sources of 1.5-μm radiation from tensile-strained InGaAs wells grown on InP substrate [23] or from tensile-strained high n-doped Ge on Si substrate [24].

In summary, we present the conception and design principles of semiconductor light sources with current injection based on ultra-long-range SPs on 1D PC surfaces. A particular design of ultra-LRSP-based devices for $\lambda = 690\,\text{nm}$ is considered and the propagation characteristics of the LRSP waves in the device is analyzed. It was shown that the edge reflection of the LRSP is low and the light extraction efficiency is high in the LRSP-based devices because the LRSP propagation constant is close to the RI of air. Optical feedback and LRSP lasing in these devices may be obtained without the use of "etch-and-regrow" processes, but by deposition of the grating on the external metal surface of the 1D PC.

References

[1] V. N. Konopsky and E. V. Alieva, Phys. Rev. Lett. **97**, 253904 (2006).

[2] H. Raether, *Surface Plasmons* (Springer, Berlin, 1988).

[3] A. Köck, W. Beinstingl, K. Berthold, and E. Gornik, Appl. Phys. Lett. **52**, 1164 (1988).

[4] A. Köck, E. Gornik, M. Hauser, and W. Beinstingl, Appl. Phys. Lett. **57**, 2327 (1990).

[5] S. Gianordoli, R. Hainberger, A. Köck, N. Finger, E. Gornik, C. Hanke, and L. Korte, Appl. Phys. Lett. **77**, 2295 (2000).

[6] D. J. Bergman and M. I. Stockman, Phys. Rev. Lett. **90**, 027402 (2003).

[7] M. Noginov, G. Zhu, A. Belgrave, R. Bakker, V. Shalaev, E. Narimanov, S. Stout, E. Herz, T. Suteewong, and U. Wiesner, Nature **460**, 1110 (2009).

[8] J. B. Khurgin and G. Sun, Opt. Express **20**, 15309 (2012).

[9] D. Sarid, Phys. Rev. Lett. **47**, 1927 (1981).

[10] P. Berini, Adv. Opt. Photon. **1**, 484 (2009).

[11] I. De Leon and P. Berini, Nature Photonics **4**, 382 (2010).

[12] P. Berini and I. De Leon, Nature Photonics **6**, 16 (2012).

[13] R. Flynn, C. Kim, I. Vurgaftman, M. Kim, J. Meyer, A. Mäkinen, K. Bussmann, L. Cheng, F.-S. Choa, and J. Long, Opt. Express **19**, 8954 (2011).

[14] P. Yeh, A. Yariv, and C.-S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).

[15] P. Yeh, A. Yariv, and A. Y. Cho, Appl. Phys. Lett. **32**, 104 (1978).

[16] V. N. Konopsky and E. V. Alieva, Opt. Lett. **34**, 479 (2009).

[17] V. N. Konopsky and E. V. Alieva, Anal. Chem. **79**, 4729 (2007).

[18] M. Kaliteevski, I. Iorsh, S. Brand, R. Abram, J. Chamberlain, A. Kavokin, and I. Shelykh, Phys. Rev. B **76**, 165415 (2007).

[19] V. N. Konopsky, New J. Phys. **12**, 093 006 (2010).

[20] A. R. Adams, IEEE J. Sel. Topics Quantum Electron. **17**, 1364 (2011).

[21] D. Bour, D. Treat, K. Beernink, R. Thornton, T. Paoli, and R. Bringans, IEEE Photon. Technol. Lett. **6**, 1283 (1994).

[22] F. Yang, J. R. Sambles, and G. W. Bradberry, Phys. Rev. B **44**, 5855 (1991).

[23] G. Jones, A. Smith, E. O'Reilly, M. Silver, A. T. Briggs, M. Fice, A. R. Adams, P. D. Greene, K. Scarrott, and A. Vranic, IEEE J. Quantum Electron. **34**, 822 (1998).

[24] J. Liu, X. Sun, R. Camacho-Aguilera, L. C. Kimerling, and J. Michel, Opt. Lett. **35**, 679 (2010).