Semiconductor DFB Laser with Plasmonic Metal Layers for Subwavelength Confinement of Light

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Abstract: An InP-based 1.55-μm wavelength DFB laser that uses surface plasmon polaritons for light confinement is proposed. A threshold current of 650 μA can be expected with the waveguide width of 200 nm and the cavity length of 76.5 μm. The device is monolithically integratable with waveguide-based optical devices.

1. Introduction

Semiconductor lasers with nanometer-sized optical cavities are indispensable components for advanced optical applications, such as on-chip optical interconnects and dense photonic integration, that need ultrasmall coherent light sources.

A promising way of building such nanocavity lasers is to make use of surface plasmon polaritons (SPPs) to confine light in a small volume beyond the diffraction limit. A number of groups have made lasers with this idea; the examples are a microdisk laser with one-side metal coating [1] and a CdS nanorod-on-silver laser [2]. These devices are one step closer to the development of nanocavity lasers but incompatible with monolithic integration with other waveguide-based optical devices.

To make an edge-emitting nanocavity laser integratable with other optical devices, Hill and others proposed a metal-insulator-metal structure with periodic plasmonic gaps [3]. Their device, however, requires tight fabrication tolerances for the confinement of light [4] and therefore is still in the experimental stage. To develop a more feasible device, we here present a novel structure, a semiconductor distributed-feedback (DFB) laser with strong confinement induced by SPPs, designed for use at 1.55-μm wavelength.

2. Device Structure

Our device combines a semiconductor diffraction grating for longitudinal feedback of light and two SPP layers for subwavelength transverse confinement. Figure 1 shows the structure. The core is an active waveguide consisting of a GaInAsP double-quantum-well (DQW) layer and two GaInAsP optical confinement layers (OCLs) sandwiched between InP cladding layers. The diffraction grating is formed by replacing the upper guiding GaInAsP with InP at regular intervals in the longitudinal direction. The waveguide is covered with metal (gold) through thin low-index dielectric layers (SiO_2); therefore SPP layers are excited on both sides of the waveguide. This structure is less sensitive to fabrication tolerances, compared with the device reported in [3], because the metal region have only to

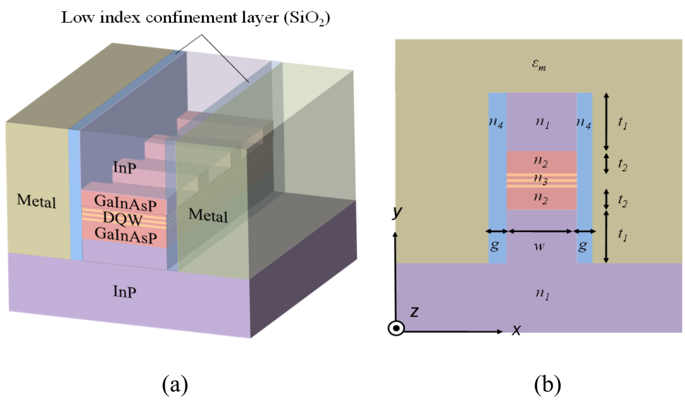

Fig. 1 Semiconductor DFB laser with tight confinement induced by SPPs: (a) three dimensional view, and (b) cross sectional view.

Table I Parameters used in Simulation

Parameter	Value
Index of InP cladding region n_1	3.17
Index of GaInAsP OCL region n_2	3.38
Index of GaInAsP DQW n_3	3.54
Index of SiO_2 gap layer n_4	1.5
Relative permittivity of Gold layer ε_m	†
Thickness of InP cladding t_1	300 nm
Thickness of InGaAsP OCL t_2	100 nm
Thickness of well/barrier in DQW	6 nm / 9 nm
Width of the waveguide w	100 - 300 nm
Width of the SiO_2 gap g	10 -100 nm

†Relative permittivity is defined by the Drude model.

confine light with its SPPs and is not concerned with longitudinal feedback of light, which is performed by the semiconductor DFB structure.

3. Mode Field Confinement

We first simulated the mode confinement in the device. The structure of the device assumed in this paper is depicted schematically in Fig. 1(b). The structural parameters we used were: (i) lower cladding layer: 300-nm thick InP (refractive index $n = 3.17$), (ii) lower OCL: 100-nm thick GaInAsP (bandgap wavelength $\lambda_g = 1.2$ μm, n = 3.4), (iii) GaInAsP DQW layer: 30-nm-thick, $\lambda_g = 1.55$ μm), (iv) upper OCL: 100-nm-thick GaInAsP ($\lambda_g = 1.2$ μm, $n = 3.4$), (v) upper cladding layer: 300-nm thick InP ($n = 3.17$), (vi) metal region consisting of gold, and (vii) low-index dielectric layer consisting of SiO_2 (n = 1.5). The width w of the waveguide and the gap width g of the SiO_2 layer were changed as parameters to find the optimal structure.

For simulation, we used the finite-element method (FEM) with the reflectionless perfectly matched layer (PML) boundary conditions for outgoing radiation. We also used a nonuniform computational mesh. The minimum separation between adjacent mesh points in the metal region was set to 10 nm, which is much smaller than the penetration depth of plasmon fields in gold. All parameters used in this simulation are summarized in Table I.

Figure 2(a) shows the distribution of time-averaged energy density of light in the device, simulated for waveguide width $w = 200$ nm and SiO_2-gap width $g = 50$ nm. The distribution profile is similar in quality to that in the Hill's device. Propagating light is confined in a small volume beyond the diffraction limit, unlike that in the structure without side metal layers (see Fig. 2(b)). Figure 2(c) shows the time-averaged energy density on the center line (or a horizontal line that passes through the center of the DQW) for various values of g. The field discontinuity of the E_x component in the refractive index of the MIM waveguide further favors a higher field peak value in the gap and minors the relative influence of the high index core field contribution in terms of the mode effective area.

Using the simulation data, we calculated the optical confinement factor in the DQW and metal region. Figures 3(a) and 3(b) show the percentage, indicated by color, as a function of waveguide width w and SiO_2-layer thickness d. To lower the threshold current for laser operation, we need both strong confinement of light in the DQW and small leakage loss of light in the metal. From these results, we found that the optimum parameters are $w = 200$ nm and $g = 70$ nm (indicated by red circles in Fig. 3).

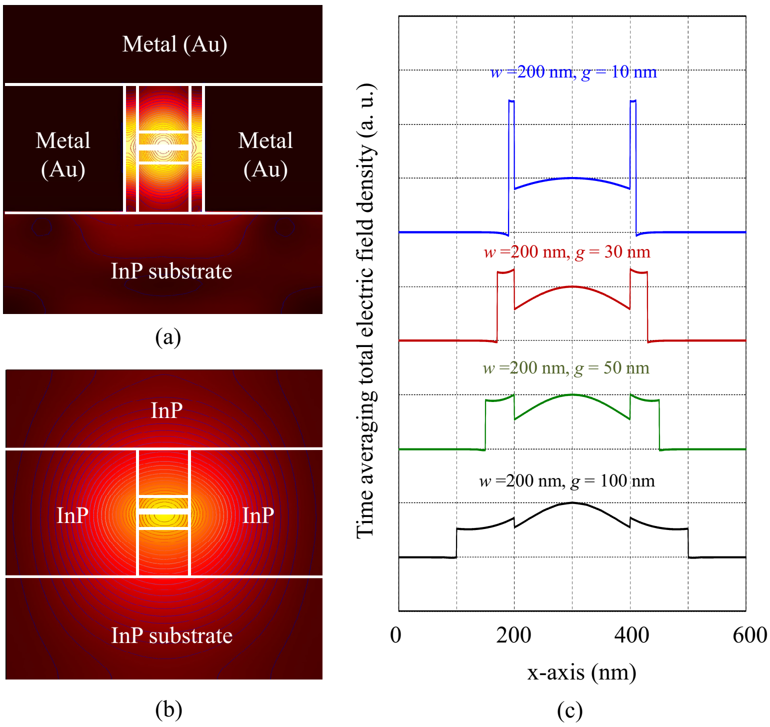

Fig. 2 Distribution profile of time-averaged energy density of light: (a) profile in plasmonic laser structure ($w = 200$ nm, $g = 50$ nm), (b) profile in reference structure without side metal layer ($w = 200$ nm), and (c) profile on center line (plasmonic laser structure, $w = 200$ nm, $g = 10$-100 nm).

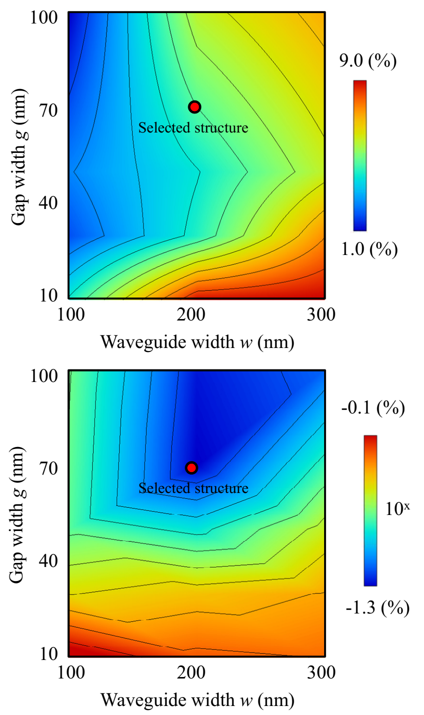

Fig. 3 Percentage of energy distribution in (a) DQW and (b) metal, as a function of waveguide width w and SiO_2-gap width g, calculated for 1.55-μm TM mode.

TABLE II MATERIAL PARAMETERS WE USED

Parameter	Value
Effective spontaneous rcombination coefficient B_{eff}	1.5×10^{-10} (cm^3/s)
Transparency carrier density N_g	1.5×10^{18} (cm^{-3})
Differential gain dg/dN	6.0×10^{-16} (cm^2)
Surface recombination velocity v_{sur}	1000 (cm/s)
Waveguide loss of DQW α_{ac}	100 (cm^{-1})
Waveguide loss of InP cladding layer α_{ex}	4.0 (cm^{-1})
Waveguide loss of metal layer α_m	†
Internal efficiency η_i	1

† We calculated from the relative permittivity defined by the Drude model.

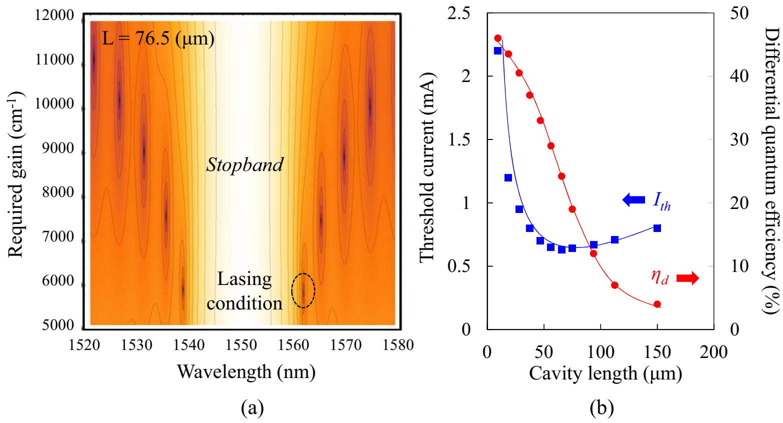

Fig. 4 Lasing threshold for 1.55-μm operation: (a) lasing-condition map for 76.5-μm cavity length, and (b) threshold current as a function of cavity length.

4. Threshold Current

We estimated the threshold currents of the device with the optimal w and g, using the coupled-wave method (CWM). The grating pitch was set at an appropriate value for 1.55-μm wavelength.

We first calculated lasing conditions for various cavity lengths. Figure 4(a) shows an example, the F_{22} element of F-matrix (which corresponds to threshold gain) for a cavity length of 76.5 μm. The value of F_{22} is indicated by light and shade as a function of wavelength and required optical gain. We can know lasing conditions from the extreme values of F_{22}. The optical gain required to compensate absorption loss in the metal is quite small because of the strong confinement of light with SPPs.

From this threshold gain, the threshold current and differential quantum efficiency were calculated for various cavity lengths by using the surface recombination velocity of 10^3 cm/s for SiO_2-passivated GaInAsP layers [4] and material parameters listed in Table II. Figure 4(b) shows the result as a function of the cavity length. It is noteworthy that sub-mA operation can be attained with a very narrow waveguide width of 200 nm by using plasmonic semiconductor DFB structure. While a minimum threshold current of 650 μA can be attained with the cavity length of 76.5 μm, an optimum cavity length for high efficiency operation would be around 30 μm.

Acknowledgment

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