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Metallic DFB lasers

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In this paper we present our latest results on the design, fabrication and characterization of metal coated DFB lasers. These devices are based on a special form of the metal-insulator-metal waveguides, which support plasmon gap modes. The distributed feedback provides control over the laser's wavelength and its emissive properties. The size of the semiconductor core can be as small as 100 nm, which is well below the diffraction limit of light. The devices operate in the near-infrared and may eventually be suitable for low-power, high-speed applications.

Introduction

Electrically pumped, metallic waveguide lasers have opened a whole new range of possibilities for integrated optics. It has been shown that despite high internal losses, lasing is possible in metallic or plasmonic cavities with dimensions well below the diffraction limit of light [1,2,3,4].

We have investigated the possibility of incorporating distributed feedback in metallic waveguides, filled with semiconductor gain medium. Such structures allow us to make waveguide lasers with control over the wavelength and to obtain single mode operation.

Structure

The devices discussed in this paper are based on a special form of the well-known M-I-M (metal-insulator-metal) waveguides. We have replaced the core with a semiconductor core, to provide gain and vertical confinement [5, 6]; we have also added two thin dielectric layers, to electrically shield the semiconductor core from the metal cladding. A schematic cross-section the structure is shown in figure 1. We will refer to this structure as an M-I-S-I-M waveguide.

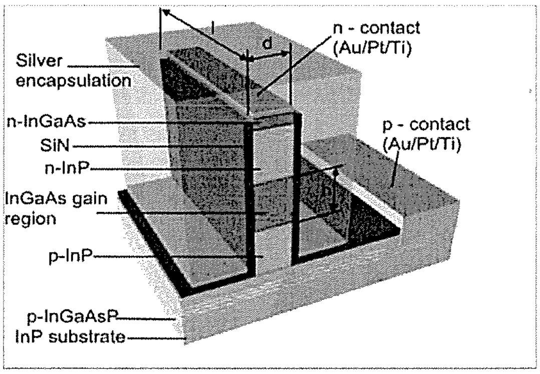

Figure 1: Schematic cross-section of a typical metallic waveguide as used in the devices discussed in this paper.

The semiconductor core consists of a double InP/InGaAs/InP hetero-junction; the width of the core is typically 80-200 nm. The dielectric layers are ±15 nm thick and consist of SiN_x. The core is encapsulated by silver, which exhibits the lowest metal loss [7] in the wavelength range of interest.

Distributed feedback is incorporated in the structure by means of a vertical groove grating in the sidewall of the semiconductor core [8]. The grating is typically 50-100 nm wider than the core waveguide. A $\lambda/4$-phase-shift is incorporated in the centre of the cavity to obtain single-mode operation at the Bragg wavelength.

Simulations

We have determined the optical response of the metallic waveguides by means of 2D and 3D FDTD simulations. The band-diagram of a 3D cross-section of a metallic waveguide shows that the waveguides support TE and TM polarized modes, depending on the width of the waveguide. The waveguides are single mode (TM_0) at 1500 nm for widths $\leq$ 160 nm.

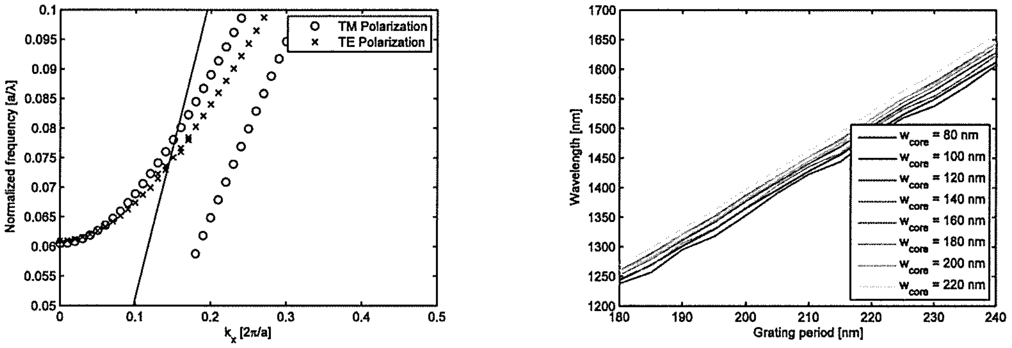

Figure 2: (a) Band-diagram of a 160 nm wide metallic waveguide, with a 20 nm bulge of the film layer a=100 nm, (b) Bragg wavelength versus grating period for various core waveguide widths, $w_{grating} = w_{core}+50$ ***nm***

We can determine the stop-band of the incorporated distributed feedback, by calculating the band-diagram of a single period. The Bragg wavelength is assumed to lie in the middle of the stop-band at the $k_x=\pi/\Lambda$ point [9]. From these calculations we have found that the Bragg wavelength can be shifted over a 300 nm range, by varying the grating period from 180 nm to 240 nm.

Assuming that the structures are designed such that the loss is dominated by the presence of the metal, we can calculate the threshold gain of a metallic DFB laser following the technique described in [10]. We find that the amount of gain required for laser operation is in the order of 1170 cm^{-1}, a value which can be obtained from bulk InGaAs material.

Fabrication

We have fabricated these structures on semi-insulating InP on which an InP/InGaAs/InP double heterojunction is grown. The wafer is patterned using a 400 nm SiO_2 hardmask in combination with a high-resolution HSQ/HPR504 bilayer resist [11]. The structures are then deeply etched with a CH_4/H_2-based ICP-RIE process [12]; after dry etching the structures, surface damage, caused by the dry etching, is removed by repeatedly oxidizing the sidewall surface and etching away the oxidized material [13]. A 15 nm thin SiN_x layer is then deposited, by means of PECVD, to protect the sidewalls and to electrically insulate the silver cladding from the semiconductor stack. After this the whole structure is covered in silver. The backside of the wafer is polished to enable characterization through the substrate and characterization via side-emission.

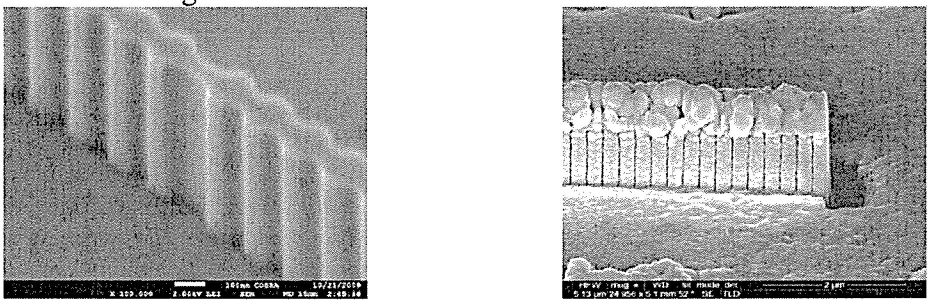

Figure 3: (a) SEM Photo of an DFB structure etched in InP and (b) SEM Photo taken after removing the silver-coated end-facet by focused ion-beam milling

Measurements

Measurements have been carried out inside a continuous flow cryostat, cooled by LN_2. The device temperature can be varied from 78K to 300K. Light emitted by the devices is collected by a high (0.42) N.A. lens and distributed over a camera with InGaAs detector array and an optical fibre. The light coupled into the fibre is lead to a LN_2 cooled spectrometer. The input-to-output loss of the setup is ±10 dB.

Both CW and pulsed current injection measurements have been carried out on devices. Results from both DFB and Fabry-Pérot type structures, with widths up to 220 nm, show that the devices predominantly operate in TM mode. Threshold currents are in the order of 400 μA for DFB type devices and approx. 800 μA for Fabry-Perot devices.

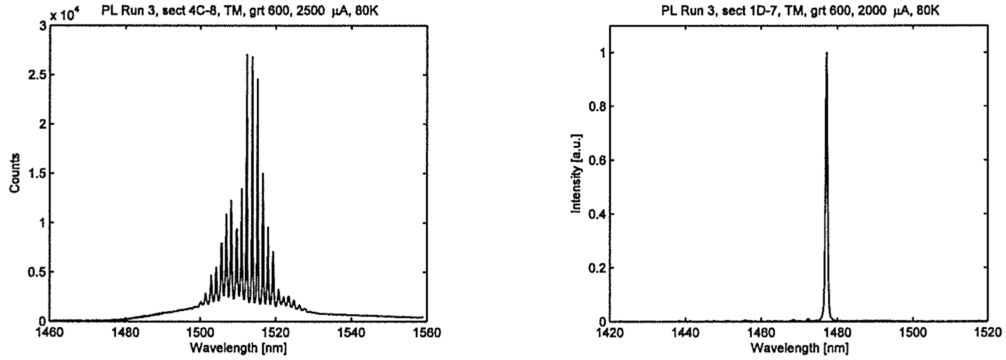

Figure 4: (a) Spectrum of a 220 nm wide Fabry-Pérot cavity, (b) Spectrum of a 140 nm wide metallic DFB laser, SMSR ± 20 dB.

Spectrally there is a clear difference between the Fabry-Perot and the DFB lasers (see figure 4). The Fabry-Perot spectrum shows ± 20 modes, spaced at 1.41 nm, corresponding to a group index of $n_g = 8.2$. The DFB laser spectra show one clear mode with at most only one significantly smaller side-mode. The suppression ratio is > 20 dB. The operating wavelength of the DFB type lasers shows a dependency on the grating period, apart from some exceptions, keeping in mind that only the grating was tuned and not the gain material (see figure 5A).

It is often argued whether metallic devices are able to operate at room temperature. 3D FDTD Simulation show that at room temperature the Q factor of a DFB cavity with a λ/4-phase-shift is approximately 300, which is sufficient to sustain laser operation. We have measured metallic DFB lasers at temperatures up to 302K, of which the results are shown in figure 5B. The spectral peak is 8 nm wide

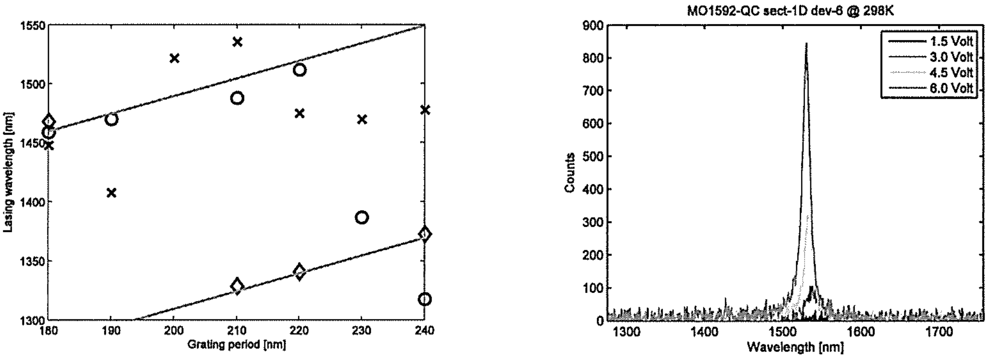

Figure 5: (a) Lasing wavelength versus grating period, (b) DFB Spectrum of a 140 nm wide laser at 298K

Conclusions

We have shown that is possible to reliably fabricate electrically pumped, metallic lasers with sub-wavelength scale waveguide widths. Distributed feedback can be incorporated in these device to obtain wavelength control and single-mode operation. A side-mode suppression ratio of ± 20 dB has been measured. The devices can sustain laser operation if the end-facets are opened. Operation at room temperature is possible for pulsed current injection.

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