Active Three-Dimensional Metal/Semiconductor Metamaterials including Ag Gratings

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Abstract

We prepare three-dimensional metamaterials consisting of alternating layers of plasmonic silver gratings and optically active semiconductor quantum wells utilizing the concept of self-rolling strained layers. Finite difference time domain calculations which assume quantum well gain obtained from measurements reveal that pumping induced transparency is expected for these structures.

1. Introduction

The fabrication of three-dimensional metamaterials is a task of interest. Three-dimensional metamaterials with bulk properties allow devices with tunable optical properties, e.g. negative index materials, cloaking devices, or hyperlenses. A hyperlens which allows sub-diffraction imaging has been built using alternating layers of metal and dieletric [1]. A three-dimensional metamaterial can be manufactured without time consuming fabrication processes by rolling-up strained semiconductor films including metallic layers [2, 3]. Using this technique alternating layers of Ag and GaAs have been rolled-up into a metamaterial with a plasma frequency tuneable in the visible regime [4].

In this paper we present the preparation of a rolled-up three-dimensional metamaterial including a silver grating and an optically active quantum well and investigate transmission enhancement through this novel material by means of finite difference time domain calculations assuming gain values extracted from experiments [5] for the quantum well.

2. Preparation

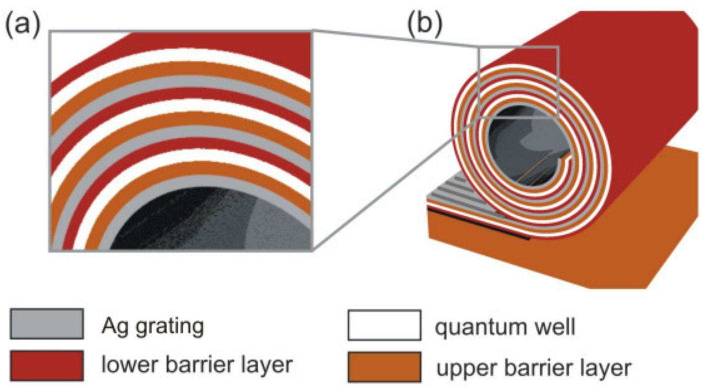

Fig. 1: Sketch of a microtube. (a) The wall of our microtube represents a radial metamaterial with alternating layers of a silver grating and an optical active quantum well. (b) The tube is fabricated based on the self-rolling of strained semiconductor layers.

Fig. 1 shows a sketch of the fabricated sample. Using molecular beam epitaxy an AlAs sacrifical layer is grown on a GaAs substrate. It is followed by a strained InAlGaAs layer which acts as a lower barrier layer, a strained InGaAs quantum well and an unstrained AlGaAs upper barrier layer. Subsequently a grating consisting of 350 nm wide trenches with 10 nm depth and 500 nm period is etched into the AlGaAs upper barrier layer and Ag is deposited onto the resulting modulated semiconductor surface by thermal evaporation. By removing the sacrificial layer, the strain energy minimises causing the system to roll up into a three-dimensional metamaterial consisting of alternating quantum well layers and Ag layers. The duration of the sacrificial layer etching determines the number of rotations and thereby the number radial metamaterial lattice cells.
Figure 2(a) sketches the cross section of a rolled-up metamaterial with three lattice cells which corresponds to the device prepared with the above parameters and shown in the scanning electron image in Fig. 2(b). The insets in Fig. 2(b) zoom into the grating in the flat area (bottom right) and in the rolled-up tubular metamaterial (upper left). The orange line in the upper left zoom in corresponds to the cross section illustrated in Fig. 2(a).

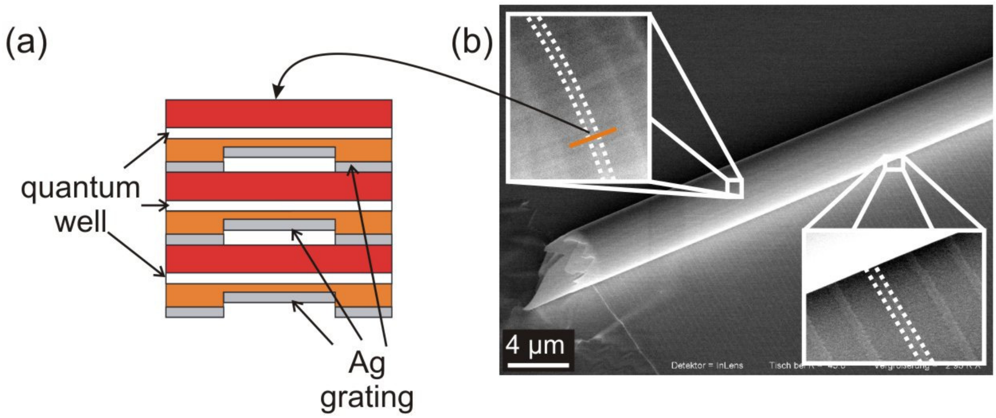

Fig. 2: (a) Sketch of a radial metamaterial consisting of alternating layers of optically active quantum wells (white) and silver gratings (grey) with three lattice cells. (b) Scanning electron micrograph of a rolled-up metamaterial corresponding to (a). The insets zoom into the grating in the unrolled area (bottom right) and in the rolled-up tubular metamaterial (upper left). For the sake of clarity one bar of the grating is indicated by white dotted lines. The orange line in the upper left zoom in corresponds to the cross section illustrated in (a).

3. Finite difference time domain simulations on transmission enhancement

Recently we experimentally proved transmission enhancement in three dimensional rolled-up metamaterials consisting of alternating layers of optically active quantum wells and planar silver films [5]. The quantum wells used for these devices and for the devices discussed here and shown in Fig. 2(b) can be reasonably modelled with an imaginary part of the refractive index of n_{im}=-0.38 if moderate pumping is assumed.

In future experiments we want to use surface plasmon polaritons (SPPs) in the rolled-up silver grating to enhance the transmission even further. For this purpose the SPPs and the Fabry-Perot resonances of the system have to be tuned to the emission energy of the quantum well, i.e. the lattice constant of the metallic grating has to be chosen appropriately to adjust the SPP resonance to the quantum well emission and the Fabry-Perot peak. For the simulations we illuminated the sample with a p-polarized broadband plane wave source and assumed a quantum well resonance wavelength of 870 nm. Figure 3(a) shows the simulated transmission versus wavelength spectrum for the above structure with a 550 nm metallic grating. For these dimensions we see that the structure exhibits a pronounced SPP

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resonance at 870 nm, along with a Fabry-Perot peak and the quantum well emission at the desired frequency.

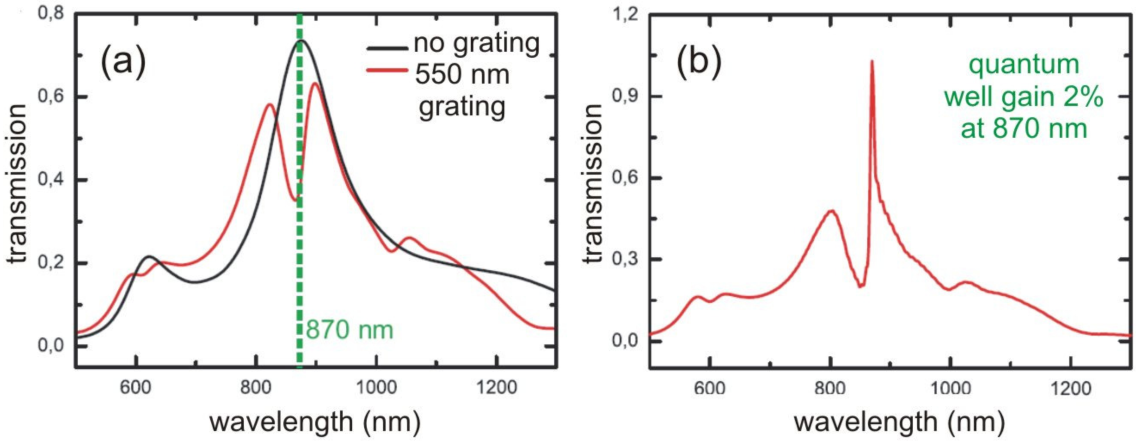

Fig. 3: (a) Transmission spectrum with 550 nm grating (red) and with a planar silver film (black) for comparison. (b) Transmission spectrum for a 550 nm grating and embedded quantum well layers with n_{im}=-0.38 corresponding to 2% gain per quantum well layer. At 870 nm transparency is reached.

In Fig. 3(b) we show the transmission spectrum with optically pumped quantum well layers, which were modelled in the simulations by applying a Lorentz-oscillator with a negative imaginary part of the refractive index. The Lorentz-oscillator strength was adjusted to correspond to a single-layer transmission enhancement of 2% found for moderate pumping in Ref. [5]. This corresponds to an imaginary part of the refractive index of n_{im}=-0.38. We observe that the transmission at the SPP resonance is drastically enhanced and pumping induced transparency is reached. The transmission enhancement is not observed when illuminating the sample with s-polarized light. Thus, we attribute the findings to the SPPs on the grating.

4. Conclusion

In conclusion we present the preparation and simulations of an optically active three-dimensional metamaterial containing quantum wells and silver gratings. In finite difference time domain simulations we observe enhanced transmission when tailoring the SPP resonance to the active region of the quantum well and illuminating the sample with p-polarized light. Since this effect is not observed when illuminating the structure with s-polarized radiation we attribute the result of enhanced transmission to the SPP resonances.

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