Rolled-up metamaterials

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Abstract

In this paper we present rolled-up optical metamaterials with integrated quantum wells as optical amplifiers. For rolled-up multilayers of a silver film and a quantum well heterostructure we find pumping induced transmission enhancement. In contrast to this, we find a pumping induced Fano shaped transmission decrease if we replace the silver film with a silver grating which corresponds to a coupling of the quantum well with surface plasmons on the three-dimensional grating structure.

1. Introduction

The production of three-dimensional metamaterials for optical frequencies requires a deliberate nanostructuring in three dimensions and is therefore one of the current challenges in the research area of metamaterials [1]. At the same time the integration of semiconductor quantum emitters into such three-dimensional metamaterials would enable new pathways towards robust active devices and the investigation of quantum emitters in media with tailored optical parameters. The method of self-rolling strained semiconductor layers [2], recently turned out to be a versatile approach to produce self-organised metamaterials, e.g. chiral metamaterials [3] or swiss rolls [4] for the far infrared frequency regime. We proposed and demonstrated to use the walls of such rolled-up metal/semiconductor structures as three-dimensional metamaterials in the optical regime. This unique approach enables the production of a three dimensional stack of metal nanostructures and molecular beam epitaxy grown semiconductor layers, which might optionally be functionalized with quantum emitters (cf. Fig. 1(a)). In a first step, we used this ansatz to produce passive three-dimensional metamaterials based on radial stacks of unpatterned silver/semiconductor layers (cf. Fig. 1(a)) and showed by transmission measurements supported by electromagnetic simulations that these structures operate as hyperlenses in the visible and near infrared regime [5]. Furthermore, we experimentally showed that the transmission through such passive structures can be optimized utilizing Fabry Pérot resonances [6] or that these structures might be patterned after the rolling-up process to obtain fish-net metamaterials with negative refractive index [7]. As the next step we discuss here the possibility to functionalize the semiconductor layer in order to integrate quantum emitters into the three-dimensional rolled-up structures.

2. Gain in rolled-up Hyperlens

We have integrated a quantum well into the semiconductor component of a rolled-up hyperlens [8] as illustrated in Fig. 1(a) to obtain transmission enhancement by optical pumping. The corresponding semiconductor heterostructure was grown by molecular beam epitaxy (MBE) and consists of an $In_{16}Ga_{84}As$ quantum well (7 nm) sandwiched between an $Al_{20}In_{13}Ga_{67}As$ barrier (23 nm) and an $Al_{23}Ga_{77}As$ barrier (21 nm). After MBE growth a 13 nm thick silver film was evaporated onto the strained semicondutor heterostructure. Subsequently, this strained Ag/semiconductor layer system was released from the substrate by etching away an AlAs sacrificial layer (white layer in Fig. 1(a)) and rolled up into a hyperlens structure. To prove pumping induced transmission enhancement in these hyperlenses with integrated quantum wells, we used a special low-temperature fiber based transmissions setup as sketched in Fig. 1(a). To maximize the quantum efficiency of the embedded quantum emitter the rolled metamaterials are cooled down to T = 10K in a helium flow cryostat. A light emitting fiber tip is positioned into the rolled-up metamaterial by piezo manipulators and the light transmitted from the fiber tip through the metamaterial is collected with a microscope objective. The same microscope objective is used to focus the pumping laser light (green line in Fig. 1(a)) onto the metamaterial in order to optically pump the quantum well. An optical microscope image corresponding to Fig. 1(a) is shown in Fig. 1(b). The pump induced transmission enhancement is obtained by comparing the transmission with a pump laser I_{TPL} and the transmission without the pump laser I_T, taking into account the photoluminescence caused by the pump laser I_{PL} and the dark count rate I_D of the detector: $\Delta T / T = (I_{TPL} - I_{PL}) / (I_T - I_D) - 1$. Figure 1(c) indeed shows a pump induced transmission enhancement of up to 10% at the emission of the quantum well (1.36 eV). This data could be well fitted with a transfer matrix ansatz modelling the quantum well with a Lorentz oscillator added to the semiconductor's permittivity. From the fit we obtained gain, i.e. amplification per length in the semiconductor material, of approximately α=2800 cm^{-1} [8].

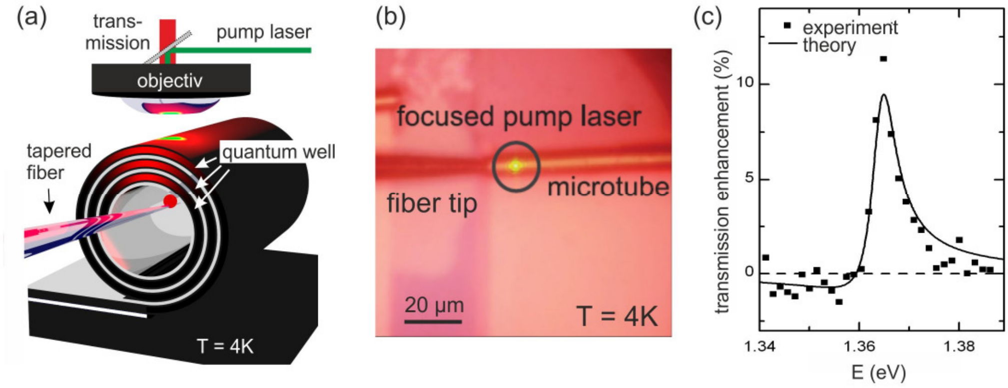

Fig. 1: (a) Sketch of a rolled-up metamaterial with an integrated quantum well. Transmission enhancement is measured with a fiber based transmission setup at liquid helium temperatures (see text). (b) Optical micrograph corresponding to (a). (c) Optical pumping induced transmission enhancement

3. Fano resonance in rolled-up plasmonic gratings with intergrated quantum wells

The possibility to pattern the metallic component before the rolling-up process enabled us to realize multilayers of a quantum well and a plasmonic grating as sketched in Fig. 2(c). A scanning electron microscopy image of the realized structure is shown in Fig. 2(a) and a focused ion beam cross-section proving the high structure quality is shown in Fig. 2(b).

We have performed finite-difference time-domain simulations and multi-layered rigorous coupled wave analysis on these structures and found that plasmonic resonances occur, whose spectral positions strongly depend on the geometric parameters of the metamaterial. The embedded quantum well was again modelled as Lorentzian resonance in the permittivity of the semiconductor component. Depending on the spectral overlap of the resonances and the assumed quantum well gain α, we have predicted characteristic Fano resonances in the pump-induced transmission change. For spectral coincidence and moderate quantum well gain a reduction in the pump-induced transmission is expected while net gain is expected for very strong quantum well gain [9].

In transmission enhancement measurements, which we performed as described above, we indeed found pronounced Fano resonances as exemplified by the symbols in Fig. 2(d). The solid line in Fig. 2(d) shows a Fano fit of our data. In the first place these Fano resonances prove the existence of the plasmonic resonances discussed above, which become experimentally accessible only due to the coupling with our quantum well. Furthermore, the fact that we observe negative transmission enhancement shows that we are in the regime of moderate quantum well gain.

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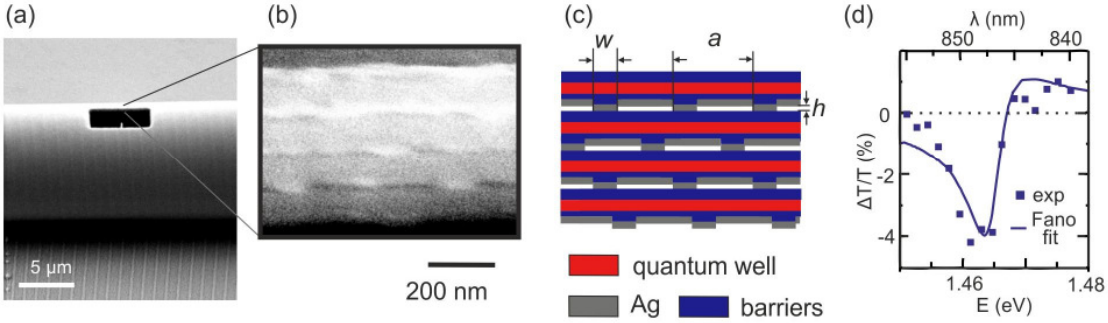

Fig. 2: (a)-(b) Scanning electron image of a rolled-up metamaterial consisting of a three-dimensional silver grating and a quantum well. (c) Schematic corresponding to (b). (d) Pumping induced change in transmission together with a Fano fit.

4. Conclusion

In conclusion, we presented optical rolled-up three-dimensional metamaterials with integrated optical amplifiers. In case of rolled-up quantum well heterostructures with integrated planar silver layers we measure a pump induced transmission enhancement of 10% corresponding to a quantum well gain of approximately α=2800 cm^{-1}. In case of rolled-up quantum well heterostructures with intergrated silver gratings we observe a characteristic Fano resonance with negative transmission enhancement which proves plasmonic resonances in the three-dimensional grating structure as predicted by simulations and gives rise to a coupling between these resonances and the quantum well. In the next step we currently work on optimized quantum well heterostructures sandwiched between plasmonic nanostructures in order to reach the regime of net gain.

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