Transmission Enhancement in Active Rolled-Up Metamaterials Utilizing Fabry-Pérot Resonances

S. Schwaiger, J. Kerbst, A. Stemmann, W. Hansen, D. Heitmann, and S. Mendach

Institut für Angewandte Physik, Universität Hamburg
Jungiusstraße 11C, 20355 Hamburg, Germany
Fax: +49-(0)40428382931; email: sschwaig@physnet.uni-hamburg.de

Abstract

Recently, we experimentally demonstrated that the transmission through a rolled-up metamaterial can be enhanced by optical excitation of an embedded quantum well. Here, we present transfer matrix method calculations on such materials modelling the quantum well gain with a Lorentz oscillator. We find that the transmission enhancement of the embedded quantum well is maximized when tuning its operation energy to a Fabry-Pérot resonance.

1. Introduction

Metamaterials consist of artificial elements with sub-wavelength dimensions. Using an appropriate arrangement of these elements, effective optical properties can be achieved which are not accessible by natural materials. However, due to Ohmic losses in the metallic compound of a metamaterial, much light is dissipated setting upper limits to the functionality of the material. A way to reduce or overcome these losses is the inclusion of an active gain medium. Recently we have realized a three-dimensional rolled-up metamaterial (RMM) with incorporated semiconductor quantum structures as an active medium which show a transmission enhancement under optical excitation [1]. Here we demonstrate by means of calculations using the transfer matrix method [2] that tuning the operation energy of the active medium to a Fabry-Pérot maximum occurring in the total thickness of the RMM, one can increase the transmission enhancement of the RMM.

2. Rolled-Up Metamaterials

Our RMMs are fabricated based on the concept of self-rolling of strained layers [3]. Using molecular beam epitaxy we grow the following layers on a GaAs substrate: A GaAs buffer layer, an AlAs sacrificial layer, a strained InAlGaAs lower barrier layer, an InGaAs quantum well, and an upper AlGaAs barrier layer. Subsequently Ag is deposited onto the semiconductor structure by thermal evaporation. In the last preparation step the AlAs sacrificial layer is removed causing the strain energy to be minimized and the system rolls up into a microtube. The wall of the resulting microtube represents metal/semiconductor RMM as sketched in Fig. 1(a). Figs. 1(b,c) show two optical micrographs of two RMMs, both consisting of alternating layers of semiconductor (51 nm) containing an active $In_{16}Ga_{84}As$ quantum well and Ag (13 nm). RMM_3 in Fig. 1(b) is rolled-up three times, while RMM_2 in Fig. 1(c) is rolled-up twice. The different numbers of rotations result in different total thicknesses. Due to the different thicknesses, the Fabry-Pérot resonances in the total thickness of the RMM occur at different photon energies explaining why RMM_3 appears green and RMM_2 appears yellow.

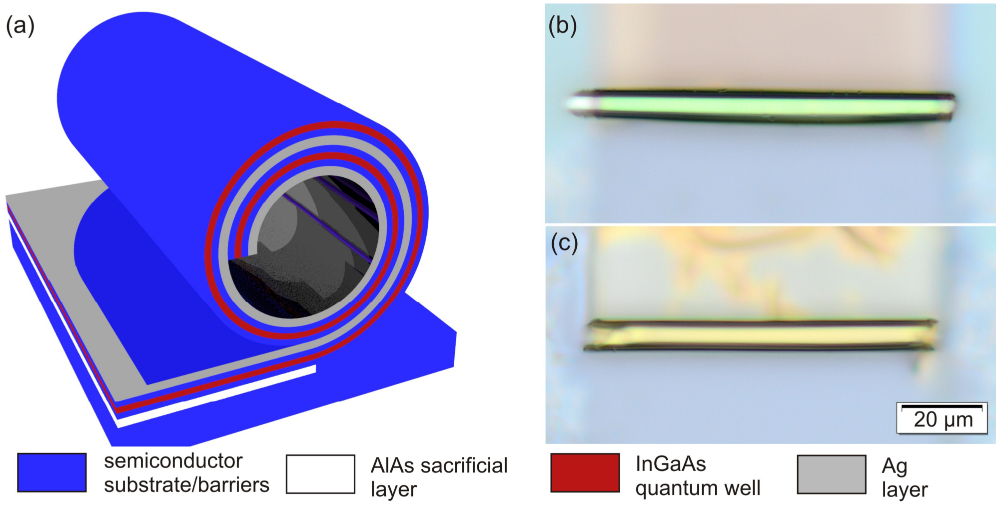

Fig. 1: (a) Sketch of a rolled-up microtube whose walls represents a rolled-up metamaterial consisting of Ag (13 nm) and (AlIn)GaAs (51 nm) containing an optically active quantum well (7 nm). (b,c) Optical micrographs of metamaterials which are rolled-up three (b) and two (c) times, respectively.

3. Transmission Enhancement in Rolled-Up Active Metamaterials

In order to calculate its transmission we model the RMM as a stack of alternating plane layers of Ag and GaAs. We calculate the transmission of the multilayered stack by the transfer matrix method [2] using the permittivities given by Ref. [4]. The transmission through RMM_5 consisting of five alternating layers of Ag (10 nm) and GaAs (51 nm) is shown in Fig. 2(a). The transmission has a maximum at E_{FPmax} = 1.205 eV with a value of T = 46% and a minimum at E_{FPmin} = 1.353 eV with T = 23%. Comparing the calculated transmission with results obtained in Ref. [5], where we experimentally demonstrated that the transmission through rolled-up metamaterials can be enhanced via Fabry-Pérot resonances, we attribute the behavior to a Fabry-Pérot resonance in the total thickness of RMM_5. In the next step we consider the optically active quantum well embedded in the semiconductor structure. For that purpose we model the permittivity of the complete active semiconductor containing the quantum well ε_{AS} with the permittivity of a Lorentz oscillator as given by following equation:

$$\epsilon_{\mathrm{AS}}(\omega) = \epsilon_{\mathrm{GaAs}}(\omega) + \left(\frac{A\omega_{\mathrm{L}}^2}{\omega_{\mathrm{L}}^2 - \omega^2 - i\omega\gamma_{\mathrm{L}}}\right), \quad (1)$$

where ε_{GaAs} is the permittivity of GaAs. ω_L is the operation frequency, γ_L the damping, and A the amplitude of the Lorentz oscillator. For terms of clarity we express A by the gain constant α given by:

$$\alpha = -\frac{A\omega_{\mathrm{L}}^2}{Re(\sqrt{\epsilon_{\mathrm{GaAs}}})c_0\gamma_{\mathrm{L}}}, \quad (2)$$

where c_0 is the speed of light. We calculate the transmission through the active RMM_5 with $A = A_1$ and normalize this transmission to the transmission through the passive RMM_5 with A = 0 to achieve the transmission enhancement $\Delta T / T$. In Fig. 2(b), $\Delta T / T$ of RMM_5 is plotted versus the photon energy E. While A_1 = 2800 cm^{-1} and γ_L = 6 meV (fitted from experimental data in Ref. [1]) is constant, we vary the operation energy from $\hbar\omega_L$ = 1.05 eV to $\hbar\omega_L$ = 1.4 eV. ΔT / T has a maximum value of $\Delta T_{max} / T$ = 25% if $\hbar\omega_L$ = 1.205 eV matches the maximum of the Fabry-Pérot resonance E_{FP}max. Compared to the Fabry-Pérot minimum at which we observe $\Delta T_{max} / T$ = 7% we determine an increase of $\Delta T_{max} / T$ by a factor of 3.2 when tuning the operation energy of the Lorentz oscillator to the Fabry-Pérot resonance.

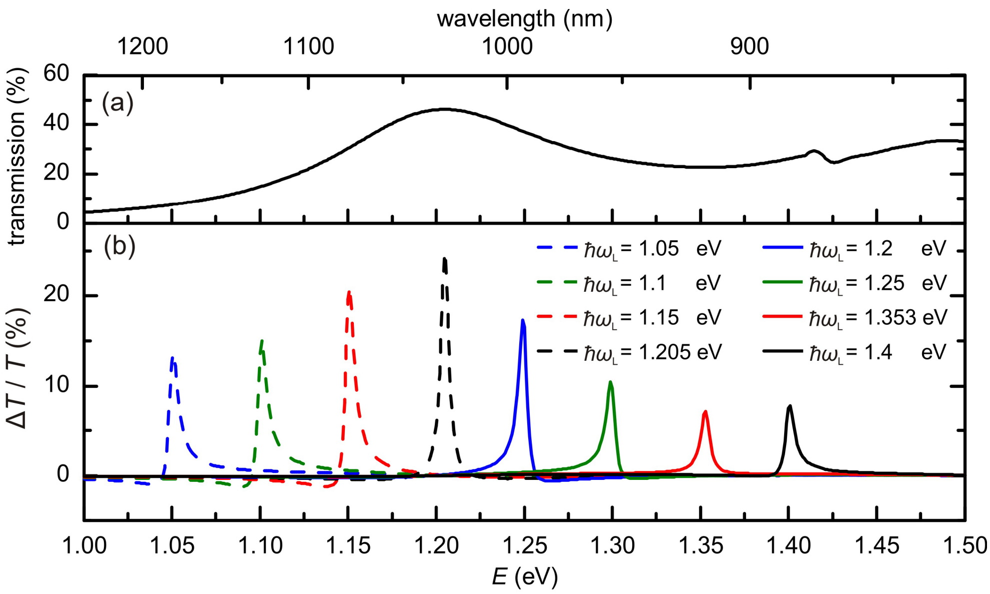

Fig. 2: (a) Calculated transmission of a multilayer consisting of five alternating layer of Ag (10 nm) and GaAs (51 nm), showing a Fabry-Pérot maximum at E_{FPmax} = 1.205 eV. (b) ΔT / T spectra achieved by replacing the passive GaAs by an active semiconductor modelled with a Lorentz oscillator. A maximum of ΔT / T = 25% is obtained when tuning the operation energy $\hbar\omega_L$ = 1.205 eV to the Fabry-Pérot maximum.

4. Conclusion

Recently we showed that optically active semiconductor quantum structures can be embedded inside a rolled-up metal/semiconductor metamaterial [1]. Here we demonstrate by calculations that the transmission enhancement of a quantum structure in the RMM can be optimized if its operation energy is tuned to a Fabry-Pérot resonance occurring in the total thickness of the metamaterial.

Acknowledgements

We gratefully acknowledge support by the Deutsche Forschungsgemeinschaft via the Graduiertenkolleg 1286 “Functional Metal-Semiconductor Hybrid Systems”.

References

[1] S. Schwaiger, M. Klingbeil, J. Kerbst, A. Rottler, R. Costa, A. Koitmäe, M. Bröll, Ch. Heyn, Y. Stark, D. Heitmann and S. Mendach, Gain in three-dimensional metamaterials utilizing semiconductor quantum structures, *Physical Review B* , vol. 84, p. 155325, 2011.

[2] M. Born and E. Wolf. *Principles of Optics*, Oxford: Pergamon Press, 1980.

[3] V. Ya. Prinz, V. A. Seleznev, A. K. Gutakovsky, A. V. Chehovskiy, V. V. Preobrazhenskii, M. A. Putyato and T. A. Gavrilova, Free-standing and overgrown InGaAs/GaAs nanotubes, nanohelices and their arrays, *Physica E,* vol. 6, p. 828 (2000).

[4] E. D. Palik, *Handbook of Optical Constants of Solids*, New York: Academic Press, 1985.

[5] J. Kerbst, S. Schwaiger, A. Rottler, A. Koitmäe, M. Bröll, J. Ehlermann, A. Stemmann, Ch. Heyn, D. Heitmann and S. Mendach, Enhanced transmission in rolled-up hyperlenses utilizing Fabry-Pérot resonances, *Applied Physics Letters*, vol. 99, p. 191905, 2011.