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Modeling terahertz plasmons in coupled semiconductor resonators

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***Abstract*—Plasmons in two-dimensional systems find applications in terahertz oscillators, detectors, filters, plasmonic crystals, etc. Numerous approaches to modeling plasmonic spectra exists, but little work has been done to compare results from theoretical calculations with each other, and so to understand their limitations. Using three different techniques (full-wave simulations, mode matching, and trasmission-line model), we analyse here a realistic structure comprising three coupled plasmonic resonators. While the results of all three models offer qualitatively similar results, revealing a rich spectrum of coupled modes, the values of the predicted resonant frequencies differ between the models. The best agreement is found between full-wave simulations and mode matching, both of which are based on rigorous solution of Maxwell's equations.**

I. Introduction

A wide range of theoretical models have been proposed to design devices that rely on plasmons in two-dimensional electron systems. Perhaps the simplest approach is to calculate the plasmon dispersion and, whenever plasmon resonances are observed, to find their resonant frequencies assuming that the resonant part of the device accommodates multiple half-wavelengths. Often, however, this approach can only provide a qualitative explanation but no quantitative agreement with experiment. More advanced models include a Fourier-integral approach [1], a transmission-line model [2], a mode-matching technique [3]–[5], and ubiquitous full-wave numerical solvers. There has, however, been little effort to compare these various approaches to each other.

This paper analyzes the resonant response of the same plasmonic device using three different approaches: a mode-matching technique, a transmission-line model, and full-wave calculations in Comsol.

II. Coupled plasmonic resonances

The device considered consists of two sections of ungated GaAs electron channels that are separated from one another by a gated section and terminated by ohmic contacts at either end, see Fig. 1(a). The lengths of the sections are $L_1 = 19.7$, $L_2 = 4.4$, and $L_3 = 48.9$ μm. The ungated electron densities are 6.5×10^{11} cm^{-2}. The gated electron density can be varied by a gate voltage in the range between 2.5 and 6.5×10^{11} cm^{-2}. These parameters reflect those of realistic devices on which we have previously published [6], [7]. The interaction between plasmons supported by each section and their reflection from the end of the sections creates a spectrum of coupled resonances.

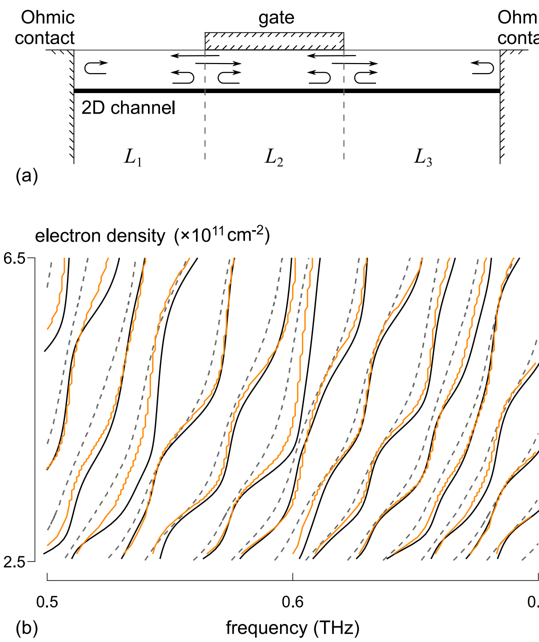

Fig. 1. Schematic of the device (a) and the spectrum of resonances calculated by different approaches (b); orange lines are from mode-matching model, black line are from Comsol, grey dots are from the transmission-line model.

The first model we used to calculate the resonant frequencies is based on mode matching [3]–[5], [7]. The fields in each section are first expanded into the waveguide eigenmodes. The fields at the junctions between the sections are then matched using the standard Maxwell boundary conditions, which allows one to determine the plasmon transmission and reflection coefficients. These coefficients are then used to construct a transmission matrix of the whole device.

The second model, developed by Aizin and Dyer [2], presents the gated and ungated sections in the form of transmission lines, in which the plasmons are described by currents and voltages. The transmission lines are characterised by matrices, which are multiplied by each other to describe the whole structure. We have here modified the original model to include different dielectric materials above the channel [see

Fig 1(a)].

Finally, we also modelled the spectrum using the eigenmode solver of the RF module in Comsol. Every channel was simulated as a thin slab with a Drude permittivity.

Figure 1(b) shows the spectrum calculated between 0.5 and 0.7 THz from the three theoretical models; the solid orange line are the solutions by mode matching, while the solid black lines are the solutions by Comsol eigenmode solver, and the grey dashed lines are obtained from the transmission-line model. Fifteen modes are predicted by mode matching and Comsol, and sixteen by the transmission-line model. Their anticrossing behaviour is typical of coupled resonances.

III. Conclusion

The results obtained from the three models behave qualitatively similarly to each other, revealing a rich spectrum of coupled plasmonic resonances. Quantitatively, the agreement is best between the full-wave simulations and mode matching. This is because they are two-dimensional models that take into account the fields in and around the channels. The simpler transmission-line model, on the other hand, assumes that the junctions between the sections are one-dimensional and relies on the continuity of the power flow through the boundary.

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