Quantum Metamaterials for Plasmonics and Strong Coupling

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***Abstract*—We show how the metamaterial concept can be extended to nanostructured solids to design new types of optical response. Using this "quantum metamaterial" approach we demonstrate a slab which supports a new type of waveguide mode which combines the advantages of strong field enhancement and efficient optical coupling previously seen with metal plasmons, with centimeter propagation distances. This mode readily "strong-couples" to the quantum transitions that we can design into the slab, allowing them to be used for processing as well as transporting information.**

***Index Terms*—Metamaterial, plasmon, strong-coupling, waveguide.**

I. Introduction

Normal Surface plasmons (SP's) are collective excitations which run along the planar interface between two materials whose dielectric constants differ in sign [1]. The electric field decays exponentially, in the direction normal to the interface, on a sub-wavelength length scale, and the resulting mode compression generates strong electric fields which are useful in sensing applications [2].

Normally the negative dielectric material is a metal, which has strong absorption losses and gives a damped mode which only propagates for some 10's μm. However, it has long been known that if a thin conducting slab is clad symmetrically by a dielectric [3], it can support a high-Q low loss plasmonic mode, or "long range plasmon" (LRP), which has the curious property that it's supported only in the presence of strong absorption in the slab; the stronger the absorption, the sharper the LRP line and the further it propagates.

The concept of a metamaterial [4] involves designing a structure which is patterned on a length scale small compared with the optical wavelength, in order to generate electromagnetic resonances. These can be used to modify the optical properties experienced by the light field in a technologically desirable way [5]. So far these structures have been patterned on a scale which, although short compared with the wavelength of light, is long compared with electron wavelengths, so the system behaves classically and can be described with the classical laws of electromagnetism. Here we extend the concept to "Quantum Metamaterials"; we use nanoscale patterning to control the electrons' behavior at the quantum level, and instead of just Maxwell's equations to design in the resonances, we also use Schroedinger's [6].

II. Results

The waveguide structures we use are fabricated using semiconductor MBE growth technology, and consist of a conducting slab made from doped multi-quantum-well (MQW) material [7]. It is symmetrically clad with thick dielectric layers of high symmetry and quality. For in-plane electric field components this MQW slab looks like a metal, with a Drude-like free-electron conductivity, and it can support a mode, which has LRP and TM-mode like properties. For any given MQW doping level there is an effective cutoff frequency, ω_{cutoff}, below which the in-plane dielectric constant flips from negative to positive which defines the mode type; however, the critical point to note though is that, provided the MQW slab is thin compared with the optical wavelength, the mode's mode volume, dispersion curve and propagation distance are unaffected by this sign change [6]. For convenience we call this mode a collective plasma resonance (CPR). Even well above ω_{cutoff} our new CPR still shows all the advantages (ease of optical coupling and strong local electric field enhancement) seen with other LRP like excitations [8]. However, because the E-field in the CPR mode points out of the slab, and hence is perpendicular to the two dimensional Drude gas, we can design out the losses with the quantum metamaterial approach, and in principle generate ultra long range plasmon excitations.

The 2D quantum nature of the electron states makes the MQW slab an extreme case of optical anisotropy, and for a in-plane polarized **E**-field, the dielectric function is a Lorentzian peak, corresponding to single electron "intersubband" transitions (ISBT's) between the confined states of the quantum wells. While the energy of the CPR depends on the macroscopic doping and thickness of the slab, the ISBT energy is governed by the nanoscopic QW thickness, so the two excitations can be matched in energy and tuned through each other in angle resolved spectroscopic measurements.

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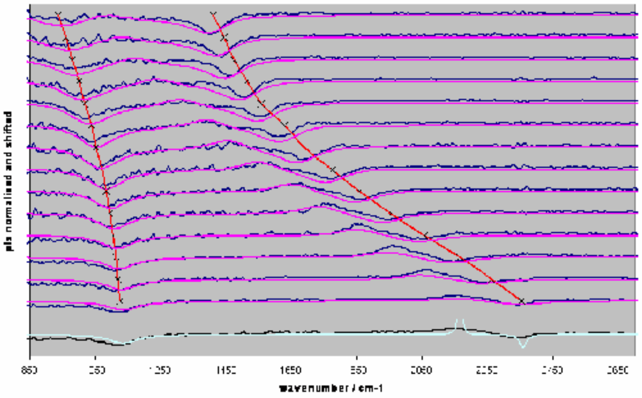

Figure 1. Angle Resolved reflectivity spectra of the MQW slab sample, showing the ISBT (~1100 cm^{-1}) and CRP (~1800 cm^{-1}) modes, anticrossing with a coupling energy of ~ 64 meV. Dashed fine lines: results of thin-film calculation, showing ISBT and CPR mode positions. Heavy solid lines are guides for the eye.

Figure 1 shows angle resolved reflectivity spectra from a d=1.8μm thick MQW slab waveguide, comprising N=50 repeats of L_{qw}=6 nm wide GaAs quantum wells, each doped to an areal electron concentration of $n_s=6.5*10^{11}cm^{-2}$, with 30 nm $Al_{0.35}Ga_{0.65}As$ barriers. For this well thickness the reflectivity spectra shows dips at ~1100cm^{-1} and ~1600cm^{-1}, corresponding to the ISBT and the CPR excitations (fig 1).

As the CPR is angle tuned towards the ISBT, the two repel and the latter red shifts by some 200cm^{-1}. Clear anticrossing behaviour appears as the two excitations are tuned through degeneracy, but the big surprise is the strength of the effect. The coupling energy, ~65meV, is some 6 times larger than either of the peak widths, which is to say that the excitations are firmly in the "strong-coupling" (SC) regime [8].

Strong coupling can normally be achieved only with sophisticated high-Q microcavity techniques. The coupling energy is commonly viewed as a Vacuum-Rabi effect, with the electronic transition being coupled to the zero-point energy of a small cavity to give a splitting energy of [9]:

$$\hbar\Omega_{VR} = 2\hbar\left[\frac{e^2 N_{qw}}{2\varepsilon_0\varepsilon_r L_{eff} m_e} f_{ex}\right]^{\frac{1}{2}}. \quad (1)$$

Where N_{qw} is the number of layers in the stack, ε_r their mean dielectric tensor, $f_{ex}=n_s 2m^* E_{12}[z_{12}/\hbar]^2$, is the oscillator strength per well per unit area, and L_{eff} is the effective length of the optical cavity with which the electrons are coupled. The other symbols have their usual meanings. For our sample the oscillator strength can be computed, from the knowledge of the electron wavefunctions in the QW, as z_{12}= 1.90 nm, and we find that to achieve the same coupling energy with a Fabry Perot cavity as we get with our quantum metamaterial approach we would need L_{eff} <388nm. This shows that, even though we are well above the cutoff frequency ($\omega_{cutofrf}$~160cm^{-1}) with this sample, the strength of the electric fields are dramatically enhanced, much stronger than can be achieved with a Fabry Perot cavity.

The black curves in Figure 1 are the results of a transfer matrix model of the slab [6], modeling its dielectric response with a Drude function for the in-plane electric field component, and as a single Lorentzian oscillator for the perpendicular one. We use electron scattering rates inferred from the ISBT's linewidths measured under experimental conditions where the ISBT is decoupled from the CPR, and doping levels and oscillator strengths are inferred from the same data. With this present, non-optimized sample, the transfer matrix model predicts propagation distances of 2.1mm and 1.34 mm at photon energies (wavelengths) of 88meV (14 μm) and 315 meV (3.94 μm) respectively. Propagation distances up to ~121 mm are predicted with thinner structures at λ~15μm[6].

III. CONCLUSION

We have shown here how the field enhancement effects of a new form of plasmonic waveguide can be harnessed to provide a new strongly-coupled system which is robust and easily manufacturable. Moreover the CPR and ISBT excitation can be electronically tuned in and out of the SC regime with low perpendicular voltages, and potentially, very high speeds, implying that these new guided modes may be used not only to transport information, but also to process it.

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