Enhanced and suppressed transmission through metal gratings at the plasmonic band edges

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ABSTRACT

Extraordinary optical transmission through metallic gratings is mediated by Fabry-Perot cavity modes inside the apertures and surface waves propagating along the grating. Anomalous features arise in the grating transmission spectrum when the optical period for the surface wave is equal to the grating pitch. The surface waves can be plasmonic in nature or due to diffracted orders propagating parallel to the surface. At optical frequencies, plasmonic effects are well separated from Wood-Rayleigh anomalies. The plasmonic band gap properties were determined with COMSOL by propagating a plasmon on a smooth Ag surface followed with a section containing a series of air gaps. The reflection spectrum for the plasmons shows a well defined frequency gap for plasmon propagation. The COMSOL simulations for light transmitted through the grating reveal anomalies in the vicinity of the plasmonic band gap. At the center frequency of the gap where surface waves are forbidden, the transmission through the grating is very low and the reflection is 98%. Standing waves are formed at the band edges and the fields become localized. At the high energy band edge the electric field localizes in the low index medium and the magnetic field in the high index medium. The field localization reverses at the low energy band edge. As a result of the localization at the band edges, the surface plasmons couple strongly to the Fabry-Perot cavity modes at the high energy band edge leading to enhanced transmission through the grating with the opposite properties for the low energy band edge.

Keywords: surface plasmon, gratings, photonic band gap, plasmonic band gap, extraordinary transmission, photonic band edge, plasmonic band edge.

1. INTRODUCTION

The existence of surface plasmons was first predicted by Ritchie in 1957[1]. By 1968, the first evidence for a plasmonic band gap was reported in experimental studies on Al and Au reflection gratings[2]. In Ref. 2, the experimental surface plasmon dispersion relation was derived from the reflection data of p-polarized light (the electric field of the incident light was perpendicular to the grating grooves). The dispersion relation for surface plasmons on the Au grating showed clear evidence of a small gap.

In 1996, Kitson[3] fabricated a silver surface textured with an array of small hemispheres. By using a prism to couple light to surface plasmons, they were able to show the existence of a full plasmonic band gap for the silver film. In the ruled gratings of Ref. 2, the gap was only for plasmons propagating perpendicular to the grooves, in the Kitson result, there was a gap for all directions of propagation.

In most studies of plasmonic band gaps, the metal surface is continuous and the surface is typically modulated in a sinusoidal pattern or modulated by a series of rectangular grooves. The gaps in the plasmon dispersion relation are found to be dependent on the groove depth and shape[4, 5]. For transmission gratings or metal sheets containing apertures the situation becomes much more interesting. Is it possible for a surface plasmon to tunnel across an air gap and continue propagating on the adjacent surface across the gap? The tunneling of surface plasmons across a discontinuity in a metal...
film was studied theoretically in 1983 by Maradudin[6] and experimentally by Seidel in 2003[7] and 2004[8]. The results based on a 60 nm thick silver film and a wavelength of 633 nm showed that surface plasmons could tunnel across the air gap with an approximately linear relation between the width of the gap and the transmittance value.

In 1998, Ebbesen[9] observed extraordinary optical transmission through a thin metal film punctuated with subwavelength holes. Most everyone agreed that surface modes were important in the extraordinary transmission, but the details of the interactions between the surface modes and the apertures were and continue to be the subject of intensive investigations[10]. These studies stimulated new investigations of surface modes in transmission gratings. In Ref. 11 it was demonstrated that transmission through thick metal gratings with subwavelength apertures results from a combination of surface plasmon modes and Fabry-Perot cavity modes inside the apertures. For TM polarization in a parallel plate waveguide consisting of metal slabs, there is not a cutoff. Due to the impedance miss-match at the entrance and exit faces of the waveguide inside the grating aperture there are Fabry-Perot modes at grating thicknesses in half lambda increments.

In the following we will show that the coupling of the grating surface modes to the Fabry-Perot modes of the apertures in thick metallic gratings is strongly dependent on the nature of the plasmonic band gap. In particular inside the band gap where the surface modes are prohibited, the coupled to the Fabry-Perot modes is strongly reduced. At the plasmonic band edges the fields become localized due to the band edge standing wave condition resulting in enhanced coupling to the waveguide modes at the high energy band edge and suppressed coupling at the low energy band edge. The enhanced and suppressed coupling to the Fabry-Perot modes results in enhanced and suppressed transmission respectively through the grating.

2. PHOTONIC BAND GAP FOR SYMMETRIC, LOSSY STRUCTURES

Before examining the properties of the plasmonic band gap it is instructive to consider the properties of a photonic band gap. The simplest example of a photonic band gap is a 1-dimensional multilayer stack consisting of alternating layers of high and low index dielectric materials. In quarter-wave dielectric mirror, each layer has an optical thickness of one quarter of the wavelength yielding a period of one half-wave. The term “symmetric” refers to the fact that the optical path in each dielectric layer is equal. Associated with the unique properties of the band gap are the properties of the photonic band edge.

![Graph showing transmittance, reflectance, and absorptance of a 10 period, quarter-wave stack with refractive indices of 1.5+i0.01/1.8+i0.0 and thicknesses 167 nm/138 nm respectively.](image)

Fig. 1) Normal incidence transmittance, reflectance, and absorptance of a 10 period, quarter-wave stack with refractive indices of 1.5+i0.01/1.8+i0.0 and thicknesses 167 nm/138 nm respectively. Note the pronounced maximum in the absorptance at the high energy photonic band edge.
The band edge refers to the transmittance maxima located on either side of the band gap. At the band edges the group velocity reaches a minimum and the fields become quasi-standing waves inside the periodic stack. In addition, the magnetic and electric fields are amplified with respect to the incident fields.

If one of the dielectrics constituting the stack is lossy (absorptive) then the band edge transmittance will be significantly altered. Fig. 1 shows the transmittance, reflectance, and absorptance of a 10 period, symmetric stack made up of a lossless high index dielectric and a lossy low index dielectric. The spectra were calculated with a commercial thin film code TFCALC. Obviously the overall transmittance is reduced due to the losses, but the band edges show the properties of field localization. The absorptance spectrum shows a noticeably larger loss at the high energy band edge compared with the low energy band edge. This due to the fact the electric field localizes in the low index layers at the high energy band edge and localizes in the high index layers at the low energy band edge. One other point about the spectra of Fig. 2 is that the reflectance for the dielectric stack with loss is nearly identical to reflectance of an equivalent stack without the loss.

2. PHOTONIC BAND GAP FOR ASYMMETRIC, LOSSY STRUCTURES

Next consider a dielectric stack that is extremely asymmetric with one of the dielectrics having a much longer optical path than the other. The spectra for a 10 period stack having a high index dielectric with an optical path 15 times longer than the low index layer are plotted in Fig. 2. The first noticeable feature of the spectra is that additional gaps are formed at half-wavelength intervals instead of full-wave intervals as in Fig. 1 for the symmetric stack. The overall depths of the photonic band gaps are smaller than in Fig.1 due to the smaller index contrast used in Fig. 2. With the exception of the additional band gaps for the asymmetric structure, the band edge properties are very similar to the symmetric case with more loss at high energy band edge. Also the reflectance for the asymmetric stack with and without loss is identical. The conclusion is that although the band edge transmittance and absorptance is highly dependent on the losses, the reflectance spectra give a good indication of the gap width and position independent of the losses.

![Fig. 2](image-url)

Fig. 2) Normal incidence transmittance, reflectance, and absorptance spectra of a 10 period, asymmetric stack with loss and without loss. The loss is only in the low index layers. For the stack without loss, the refractive indices are 1.0/1.1 and the thicknesses are 32 nm/534 nm respectively. The lossy structure is the same except the low index dielectric constant is 1.0+i0.05.
3. PLASMONIC BAND GAP FOR ASYMMETRIC, LOSSY STRUCTURES

The properties of the plasmonic band gap were calculated by COMSOL, a commercial finite element code. Surface plasmons propagate on the surface of a metal and the propagation losses are strongly wavelength dependent. Fig. 3 shows the transmittance of a surface plasmon propagating on a Ag/air interface over a distance of 38 μm. At a wavelength of 600 nm, 90% of the energy is dissipated due to absorption losses. Beyond 900 nm the losses are much lower and not as sensitive to the wavelength.

![Fig. 3) Transmittance of a surface plasmon propagating on a smooth Ag/air interface over a distance of 38 μm.](image)

Due to the surface plasmons strong dispersive properties and large losses in the visible, we first consider a plasmonic band gap structure in the near infrared. The structure consists of a semi-infinite thick slab of Ag having 10 periods of slits with a slit width of 32 nm and a period of 1132 nm. The metal is discontinuous and the slits support a TEM waveguide mode. In the simulation, a surface plasmon propagates a few microns on a smooth surface before encountering the slits. Fig. 4 shows some results of the simulation, in particular the reflection, the absorption in the metal, and the amount of energy that is coupled into the TEM waveguide mode of the slits. The reflection spectrum shows a prominent peak at a wavelength close to the period of the grating indicating a plasmonic band gap. The absorption spectrum is the energy absorbed in the metal including the grating surface as well as the walls of the apertures due to coupling to the TEM waveguide mode of the slits. The absorption increases for wavelengths on the high energy side of the band gap. The spectrum of the energy propagating in the slits shows very strong coupling from the surface plasmon to the TEM waveguide mode of the slits. For as few as ten periods nearly 25% of the energy is propagating inside the waveguides. For thick transmission gratings where the waveguide modes are on the order of the wavelength or more this result show that once a surface mode is excited it can efficiently transfer energy into the slit and eventually excite surface modes on the other side of the grating. Equally important is the disparity in the coupling efficiency on either side of the plasmonic band gap. The localization of the fields and the low group velocity at the band edges causes enhanced coupling at the high energy band edge and reduced coupling on the low energy band edge. As illustrated in Fig. 2, the higher absorption in the low index region of the asymmetric photonic band gap is a result of the field localization at the band edge. For the surface plasmon propagating on the grating surface, the extra loss on the high energy side of the plasmonic band gap is due to the strong coupling to the TEM waveguide mode of the slits.
Fig. 4) Spectra for a surface plasmon launched on a smooth Ag/air interface and then propagating across 10 slits of width 32 nm and period 1132 nm. The reflection spectrum shows the position of the plasmonic band gap. The total energy absorbed by the metal and the energy propagating in the slits is greatly enhanced on the high energy side of the band gap due to field localization at the band edges.

4. TRANSMITTANCE THROUGH A THICK METAL GRATING

Next we consider a grating with a period of 566 nm and slit width of 32 nm. In the visible region where there is stronger penetration of the surface plasmon fields into the metal, the effective index for the plasmon is large enough to separate the Wood’s anomaly from the plasmonic band gap. The surface plasmon reflection spectra are plotted in Fig. 5 for a grating 300 nm thick and a semi-infinite grating thickness.

Fig. 5) Reflection spectra for a surface plasmon launched on a smooth Ag/air interface and then propagating across 60 slits of width 32 nm and period 566 nm. The plasmonic band gap is centered at ~585 nm for the case of a 300 nm thick grating and a semi-infinite thick grating.
The presence of a photonic band gap would be expected to influence the overall transmittance through the grating. Fig. 6 shows the transmittance through the grating at normal incidence and TM polarization. The grating parameters are the same as in Fig. 5 and a 300 nm thickness. The choice of TM polarization allows coupling to the TEM waveguide mode in the slits. The broad minimum in the transmission is due to the surface plasmon band gap which prohibits the excitation of surface plasmons. At the low energy plasmonic band edge near 600 nm, the standing wave condition localizes the fields to inhibit coupling to the TEM waveguide modes inside the apertures. At the high energy plasmonic band edge near 570 nm, the field localization enhances the coupling to the waveguides. At the onset of first order diffraction near 566 nm, Wood’s anomaly reduces the transmittance.

![Graph showing transmittance at normal incidence and TM polarization for a grating with a period of 566 nm, slit width 32 nm, and thickness of 300 nm. The overall transmission band from 500 nm to 650 nm is due to a Fabry-Perot cavity mode inside the slits. The modulation in the spectra is due to the plasmonic band gap and associated band edge effects and Wood’s anomaly at the onset of first order diffraction. The small maximum at the onset of the first order diffraction is an artifact due to a small portion of the near-field being summed in the transmitted energy.](image)

5. SUMMARY

Extraordinary optical transmission through thick metallic gratings is a complicated interaction of Fabry-Perot cavity modes, Wood’s anomaly, and surface plasmons and associated band gap and band edge effects. In this work we have attempted to distinguish the plasmonic effects from the Wood’s anomaly and thereby illustrate the nature of the influence of surface plasmons on the grating transmission. In particular, the surface plasmon band gap inhibits surface modes and the coupling to the TEM waveguide modes in the slits resulting in low transmission. At the plasmonic band edges the low group velocity and field localization leads to strong coupling to the waveguide modes at the high energy band edge and weak coupling at the low energy band edge.
REFERENCES