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Experimental Observation of Broadband Extraordinary Transmission at the Plasmonic Brewster Angle in Metallic Gratings

M.J. Bloemer, *N. Akozbek, **R.H. Trimm, *G. D'Aguanno, and *N. Mattiucci
 Department of the Army, C.M. Bowden Facility, Redstone Arsenal, AL 35898;
 *Nanogenesis Division, Aegis Technologies, Huntsville, AL 35806;
 **Miltec, 678 Discovery Drive, Huntsville, AL 35806
 Mark.Bloemer@us.army.mil

Abstract: Extraordinary transmission through thick gratings results from Fabry-Perot resonances inside the apertures and is narrowband. We report observation of extremely broadband transmission through thick gratings at angles of incidence related to a plasmonic Brewster's angle. OCIS Codes: 160.1245

Extraordinary transmission through subwavelength apertures in metal screens was reported by Ebbesen *et al.*[1] over ten years ago. Since that time, numerous papers have been published on a variety of geometries[2]. While the extraordinary transmittance can be very large the spectral width of the transmission is limited. A recent theoretical paper by Alu *et al.*[3] on thick metal gratings predicted a new mechanism for extraordinary transmission that is extremely broadband and is analogous to the Brewster angle. At the Brewster angle of incidence, the reflectivity of p-polarized light (electric field in the plane of incidence) goes to zero. Alu *et al.* predicted a similar Brewster-like angle for p-polarized light incident on a metal grating. At long wavelengths where metals are highly reflective, the implications of a Brewster angle for a metallic grating is that the transmittance will be close to 100% and independent of the grating thickness.

In order to experimentally verify the predictions of a Brewster angle for a grating at microwave frequencies, we assembled a grating consisting of Al bars that were 1 inch thick and 1/8 inch wide. The overall dimensions of the grating were 2 ft. high and 3 ft. wide. The bars were held in place by metal rods at the top and bottom of the grating. The width of the aperture could be adjusted by spacers placed between the individual bars. Microwave transmission measurements were performed with a network analyzer and a set of microwave horn antennas in the frequency range of 16-40 GHz. We measured the transmittance as a function of frequency and angle up to angles of 85 degrees. The results are shown in Figure 1.

The transmittance plots in Figure 1 show two distinct transmission phenomena. At angles of incidence up to 40 degrees the transmission spectrum is dominated by Fabry-Perot modes inside the apertures. These modes are insensitive to angle but are narrow band in frequency. At steep angles of ~70 degrees there is a noticeable transmission band that spans nearly the entire spectral range. This transmission band is analogous to the Brewster angle.

The transmittance through the grating was calculated by two separate methods. The first method was the transmission line method[3]. The results are plotted in the upper right in Figure 1. This simple analysis captures most of the features seen in the experimental data shown in the lower right hand in Figure 1. The transmission line analysis does not take into account any diffraction from the grating. The onset of first order diffraction can be seen in the experimental data beginning at 30 GHz for steep angles of incidence. For more shallow angles of 40 degrees, the onset of first order diffraction occurs at 40 GHz.

A second calculation that takes into account diffraction is based on the Fourier Modal Method(FMM)[4]. The results of the calculation are shown in the bottom left of Figure 1. The results of the FMM describe the experimental results very well.

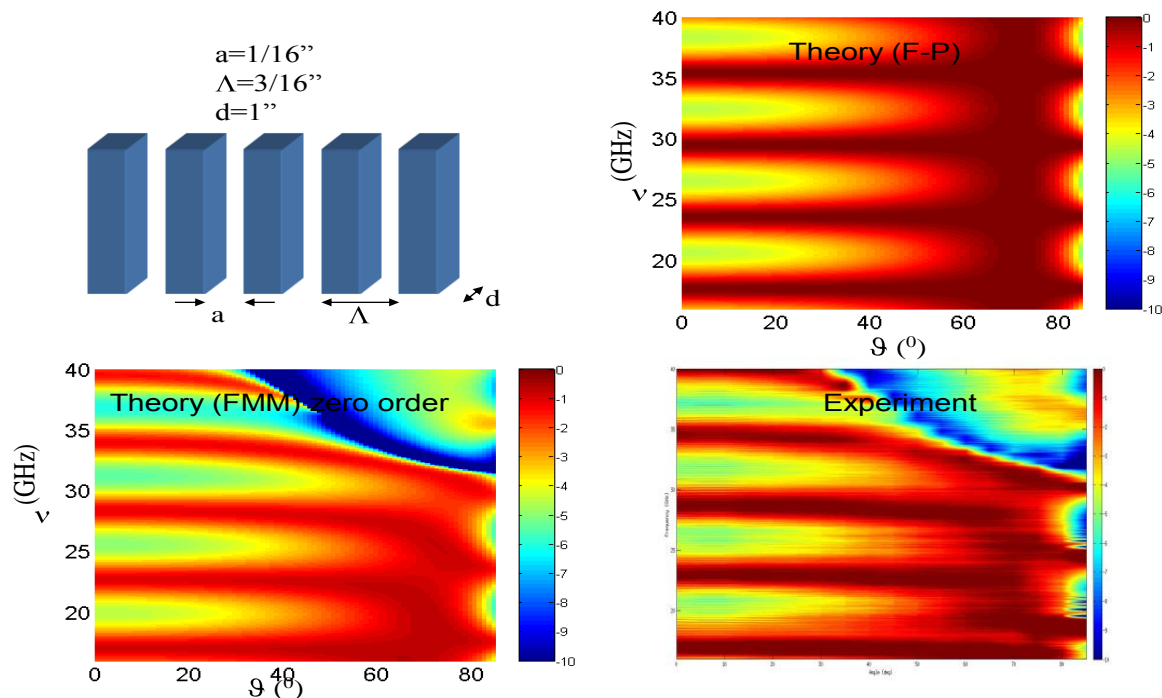


Figure 1) Transmittance through a 1 inch thick Al grating with apertures of 1/16 inch. The grating period is 3/16 inch. The microwave radiation was polarized with the electric field perpendicular to the metal bars, p-polarization. Upper left: grating diagram. Upper right: Theoretical transmittance in dB for the grating using the transmission line approach. Lower left: Theoretical transmittance for the grating using a frequency modal method (FMM). Lower right: Experimental transmittance of the grating.

It is worthwhile noting that at the lower frequencies, the width of the aperture is 50 times smaller than the wavelength. In addition, considering that the open area of the grating is only 33% it is remarkable that the transmittance through the grating is nearly 100%. It is expected that the transmittance at the Brewster angle is near unity from the onset of first order diffraction at 30 GHz to dc. The plasmonic Brewster angle is expected to be valid for metals up to visible frequencies as long as the grating period is smaller than the wavelength.

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[2] F.J. Garcia-Vidal, L. Martin-Moreno, T.W. Ebbesen and L. Kuipers, "Light passing through subwavelength apertures," *Rev. Mod. Phys.* **82**, 729-787 (2010).

[3] Andrea Alù, Giuseppe D'Aguanno, Nadia Mattiucci, and Mark J. Bloemer, "Plasmonic Brewster Angle: Broadband Extraordinary Transmission through Optical Gratings," *Phys. Rev. Lett.* **106**, 123902 (2011).

[4] G. D'Aguanno, N. Mattiucci, A. Alù, and M. J. Bloemer, "Quenched optical transmission in ultrathin subwavelength plasmonic gratings," *Phys. Rev. B* **83**, 035426 (2011).