

Study of Leaky Waves Responsible for Terahertz TE Extraordinary Transmission

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Abstract— Extraordinary transmission (ET) via transverse electric (TE) modes through dielectric-backed periodic subwavelength slit arrays is largely owed to the leakage of energy from waves guided by the structure. This phenomenon is investigated in order to shed light on the leaky wave mechanism. Both angular transmission and temporal measurements are undertaken, revealing the origin of both the modes developed in the structures and the behaviour of the energy coupled to these modes.

Keywords— extraordinary optical transmission, leaky waves, dielectric slab mode, slit array

I. INTRODUCTION

Extraordinary transmission (ET) of radiation through subwavelength periodic arrays attributed to transverse magnetic (TM) modes is a phenomenon which, thus far, has been largely studied and understood [1]. In contrast, ET via transverse electric (TE) modes has been somewhat neglected, since TE grounded dielectric slab modes are trapped [2]. The addition of periodic patterning, however, enables these modes to become leaky, allowing free space modes to couple to these TE modes [3]. Leaky waves arise in periodic structures due to the periodic perturbations (slits, in our case), which cause the mode in the structure to be formed of an infinite number of space harmonics, namely Floquet modes [2]. If one of the modes is a fast wave, the mode is considered leaky, and hence radiates energy, resulting in ET.

ET is a phenomenon utilized in technologies such as sensing and applications in quasi-optics [1] [4] [5]. It is therefore fundamental to characterize the behaviour of leaky waves in such structures to allow for optimal design and use. In this study a time domain spectroscopy (TDS) system (all fibre-coupled THz time-domain spectrometer TERA K15) is used to study truncated aluminium periodic slit arrays at terahertz frequencies. The arrays have lattice period $d_x = 0.6$ mm, slit width $w = 0.22$ mm and slit length $l = 70$ mm (see Figure 1). The arrays were patterned onto dielectric slabs of polypropylene (PP) ($\epsilon_r = 2.25$ and loss tangent $\tan \delta = 0.001$). The incident beam was collimated, providing a frequency-dependent beam waist of $\omega_x = 8$ mm at 0.5 THz. CST Microwave Studio® simulations are carried out to support the results and to better understand leaky wave behaviour.

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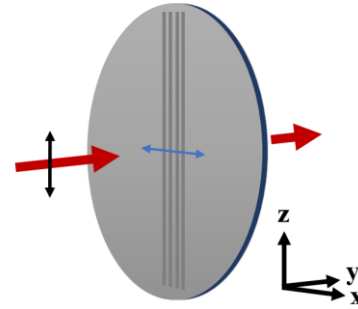


Fig. 1. Diagram of sample with metallic periodic layer (grey) and grounded dielectric slab (dark blue). The incident beam was polarised along the z-direction, propagating in the y-direction. The leaky waves propagate along the $\pm x$ -direction, indicated by the blue arrows.

II. RESULTS AND DISCUSSION

A. Angle-Resolved Transmission

The angular dependence of transmission through the structure provides an insight into the origin of the emission, namely, the Floquet modes. This stems from the dispersion relation of these modes within the periodic region. Figure 2 presents a H -plane radiation diagram for samples with 30 slits, with dielectric slab thicknesses of 102 μm and 188 μm .

From the results for the thinner dielectric slab, frustrated ET can be observed [6]–[8]. The development of the TE modes are highly dependent on the thickness of the dielectric slab, since there exists a cut-off frequency which depends on this thickness, for which below this frequency the mode is not fully developed.

The cut-off frequency for TE surface mode on a grounded dielectric slab can be calculated from (1) [2],

$$f_c = \frac{(2n-1)c}{4t_d\sqrt{\epsilon_r-1}}, \quad n = 1, 2, 3, \dots \quad (1)$$

where n is the mode number, t_d is the dielectric thickness and ϵ_r is the relative permittivity of the dielectric material. For a frequency of 0.44 THz (measured as the frequency of ET for the $m = -1$ space harmonic) a threshold dielectric thickness of 150 μm is obtained ($n = 1$). This is supported by the slight reduction in ET (~ 2 dB) observed for the thinner dielectric, indicating that the thickness is below threshold, while for the thicker dielectric, the first Rayleigh-Woods anomaly (~ 0.47 THz), also known as the open stopband [9], is fully developed.

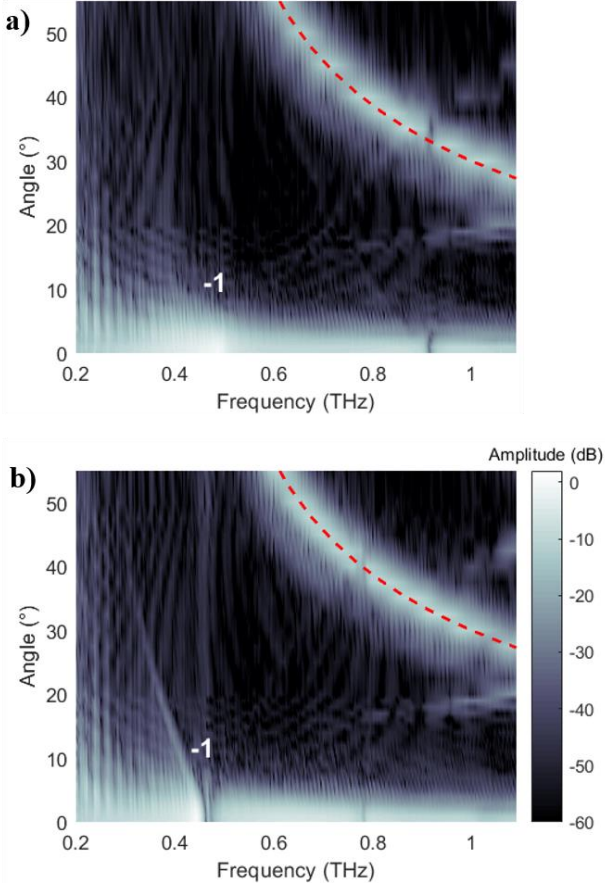


Fig. 2. Radiation diagrams for samples with 30 slits and dielectric slab thicknesses of a) 102 μm and b) 188 μm . The angular dependence of the diffraction lobe was obtained from simulations in CST Microwave Studio® and presented as a dashed line. The $m = -1$ space harmonic is labelled.

The individual Floquet modes can be identified from their angular dependence, indicated by the labels in Figure 2. At large detection angles, a diffraction lobe attributed to the interaction of the incident radiation with the periodic structure is visible. Simulations of electric and magnetic fields through the structure for swept transmission angles were carried out in CST Microwave Studio®. The peak in transmission attributed to the diffraction lobe was obtained for each angle and presented in Figure 2 as a dashed line, proving to agree well with the measurements.

B. Time-Resolved Transmission

The temporal analysis of transmission is important in understanding the behaviour of the leaky wave mechanism responsible for ET. To observe the energy retention within the system, spectrograms were obtained for normal transmission for both sample thicknesses, for arrays with slit numbers 1, 3, 7, 15, 30 and 107. From these results, the time for 1/e of the signal to decay was calculated for each sample and presented in Figure 3, at the ET frequency of 0.48 THz and 0.44 THz for the samples with thin and thick dielectric slabs, respectively.

The radiating behaviour of the leaky waves is indicated by the delayed emission of energy from the structure beyond the initial direct transmission. The length of an array with 27 slits is approximately equal to the diameter of the incident beam ($s \cdot d_x / 2\omega_x \sim 1$). The small increase in time of decay beyond 30 slits indicates that increasing the number of slits increases the coupling of energy to the structure, resulting in the leaky

waves travelling further, and hence for longer, along the structure. Saturation in energy decay time occurs above 30 slits. Saturation in transmission is reached when the array is long enough that leaky waves have explored a large enough number of slits to re-emit all the energy associated with the mode, as with TM ET [10] [11].

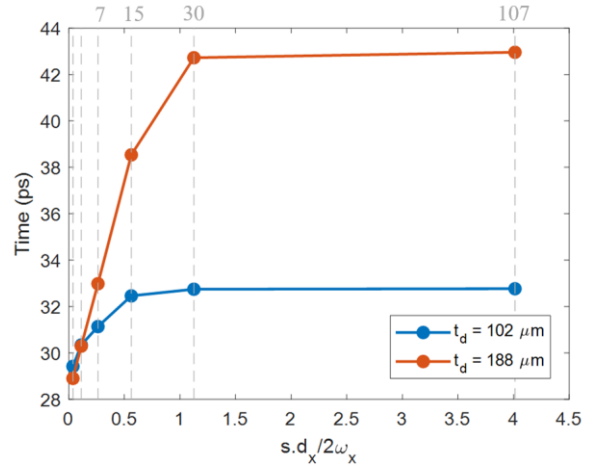


Fig. 3. 1/e energy decay time as a function of the length of the periodic array (the product of the number of slits, s , and the periodicity, d_x) normalised by the beam diameter, $2\omega_x$, for dielectric slab thicknesses $t_d = 102 \mu\text{m}$ and $t_d = 188 \mu\text{m}$. The number of slits is labelled along the top of the figure.

The substantial difference in saturation decay times for the different dielectric thicknesses can be attributed to the previously mentioned threshold thickness, whereby a defined thickness is required for the grounded dielectric mode to be fully developed, allowing for efficient coupling to the mode. An underdeveloped mode inhibits energy coupling to these leaky modes and hence less energy is available and can therefore explore a lower number of slits before dissipating.

C. Simulations

The absolute value of the electric field was calculated for the structures under investigation using the transient solver of CST Microwave Studio®. Figure 4 a) and b) present the results for the samples with dielectric slab of thickness $t_d = 102 \mu\text{m}$, while c) and d) present the results for dielectric thickness $t_d = 188 \mu\text{m}$, for 7 and 107 slits, respectively.

Comparing Figure 4 c) and d), a much larger coupling of incident field to the $m = -1$ space harmonic can be observed for a larger number of slits, resulting in increased ET, supported by the findings from the temporal analysis (Figure 3). This increase in transmission means that less energy couples to the slow confined wave travelling along the non-periodic part of the structure, indicated by the smaller electric field simulated in Figure 4 d) further away from the periodic slit array in the centre.

From Figure 4 b) and d) the requirement for a dielectric thickness larger than the threshold value is notable, with a significant reduction of coupling of the incident radiation to the leaky mode for $t_d = 102 \mu\text{m}$ (below threshold thickness), indicating the underdevelopment of the mode. For dielectric thickness $t_d = 188 \mu\text{m}$, the radiation can couple efficiently, resulting in higher ET.

Figure 5 presents the electric field obtained from the simulations, at a distance of 20 μm above the samples (y -direction) for one half of the array, providing further insight

into the spatial behaviour of the leaky waves. As demonstrated in Figure 5 a), for samples with dielectric thickness $t_d = 102 \mu\text{m}$, almost no energy couples to and propagates along the array, a result of the aforementioned underdeveloped mode. The energy at the centre is likely due to direct transmission through the slits. A much larger electric field is present at the centre of the array for samples with dielectric thickness $188 \mu\text{m}$, however, it decays at the same rate along the array for both thicknesses, the slope being determined by the leakage constant of the surface mode. In Figure 5 b) the electric field along samples with varying number of slits also decays at the same rate initially, however, the truncation of the arrays with less than 107 slits reduces the amount of energy coupling to the leaky waves, and hence it continues to propagate along the sample as a slow, non-leaky wave. The slight reduction in electric field in the region outside the periodic array is attributed to absorption by the dielectric. The electric field along the 107 slit array with dielectric thickness $188 \mu\text{m}$ decays completely before the end of the periodic region, radiating all the energy coupled to the leaky mode, achieving saturated ET.

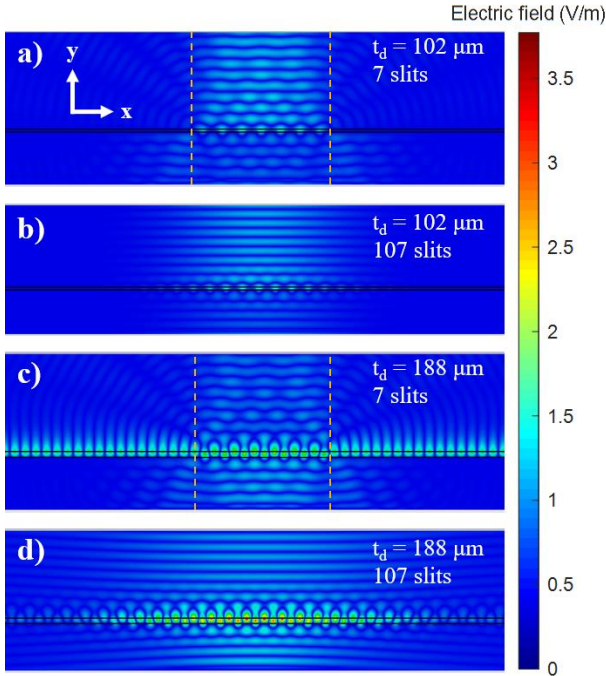


Fig. 4. Absolute electric field simulated with the transient solver of CST Microwave Studio® for samples with dielectric thickness $t_d = 102 \mu\text{m}$ (at ET frequency 0.48 THz) (a, b) and $t_d = 188 \mu\text{m}$ (at ET frequency 0.44 THz) (c, d), for 7 and 107 slits, respectively. The truncation of the 7 slit array is indicated by the yellow dashed lines. A Gaussian source is used with direction of propagation along the y-axis. The array is along the x-direction. The electric field is indicated by the colour bar.

III. CONCLUSION

The temporal and spatial behaviour of leaky waves responsible for THz ET through dielectric-backed subwavelength slit arrays has been characterised through both experimental measurements and simulations. The dependence of the thickness of the grounded dielectric slab on the development of these modes has been demonstrated, while a threshold thickness of $150 \mu\text{m}$ was calculated.

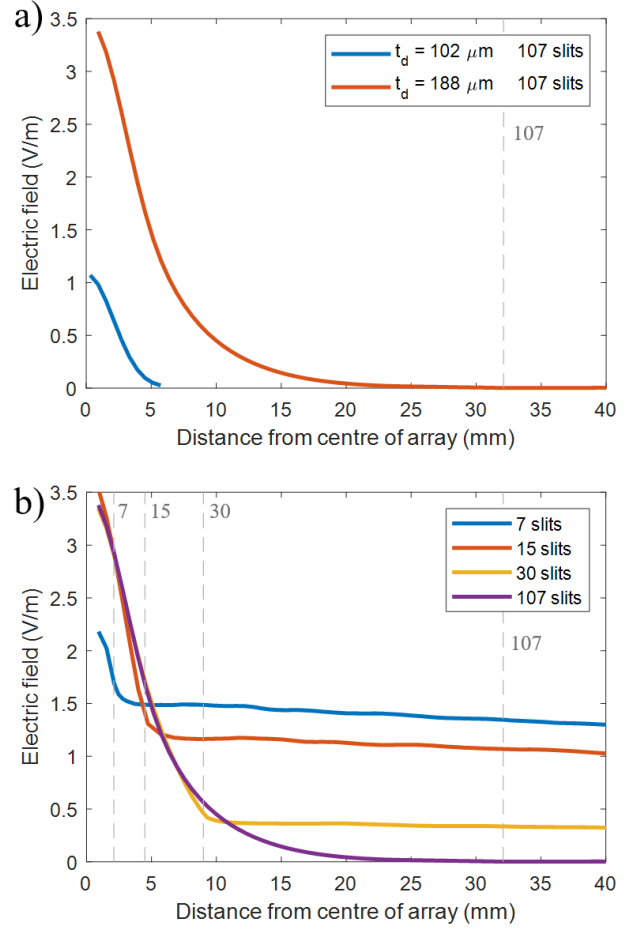


Fig. 5. Absolute electric field along one half of the array simulated in CST Microwave Studio® for samples with a) dielectric thickness $t_d = 102 \mu\text{m}$ and $t_d = 188 \mu\text{m}$ for 107 slits and b) dielectric thickness $t_d = 188 \mu\text{m}$ for 7, 15, 30 and 107 slits. The electric fields were calculated for frequency of ET for each sample (0.48 THz and 0.44 THz for $t_d = 102 \mu\text{m}$ and $t_d = 188 \mu\text{m}$, respectively). The dashed lines indicate the distance of the end of each slit region from the centre of the array. The incident beam radius is 1.5 mm .

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