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CONTROLLED RADIATION FROM DIELECTRIC SLABS OVER SPOOF SURFACE PLASMON WAVEGUIDES

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Abstract—The radiation characteristics of dielectric slabs over a transmission waveguide, based on the concept of spoof surface plasmons, are studied in this paper. The proposed structure can be used to control the radiation over a wide band of operation, whilst retaining low Side Lobe Levels (SLLs) and cross-polarization. Leaky modes, broadside radiation and directive beams at fixed angles can all be obtained using various configurations (utilising homogeneous or gradient index dielectric slabs). The proposed antenna design has attractive performance for THz detectors and transmitters.

1. INTRODUCTION

Traditionally, the existence of surface waves was originally demonstrated for dielectric materials placed over a metal surface. However, these surface waves can be also excited without the presence of a dielectric material by tailoring the metallic surface with a periodic repetition of obstacles or holes in the direction of propagation [1–3]. In recent years, the use of these surface waves to transmit energy in the THz regime has been proposed [4–6], but as early as the 50's this technology had been identified for the microwave regime by the Engineering community [7, 8]. The possibilities of designing circuitry based on this technology at THz such as power dividers, directional couplers, or waveguide ring resonators have been demonstrated with promising results [4]. It was also demonstrated that these waveguides offer a low level of loss and, in addition, they have the ability to confine the electromagnetic fields in the lateral dimension without any practical mismatch losses which arise due to the small variations in the propagation constant of the surface mode with this transversal dimension [4–6].

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However, although the properties and advantages of these structures as transmission waveguides have been demonstrated, feasible radiators for this technology have been not adequately studied. In this paper, an antenna is proposed that can be excited directly from transmission waveguides that use the concept of domino plasmons. The operation of this antenna consists of the transformation of surface waves into leaky waves, which are radiated in a certain direction. Typically, the direction of the main beam of a leaky wave antenna has a strong frequency dependance [8–12]. However, in our proposed design, due to the properties of the initial surface wave excited in the corrugations, the antenna exhibits a practically constant angle of elevation for the main beam over a very broadband of operation. For certain applications [13], this represents a clear advantage with respect to other previous leaky wave antenna designs based on metallic corrugations [8]. The radiation characteristics of a design with a GRIN (Gradient Index) dielectric slab to obtain a broadside radiation pattern is also studied. A similar approach was proposed in the 60's and 70's to excite surface plasmons in dielectric waveguides using prisms [14, 15]. However, here a more sophisticated technique is presented that allows control over the radiation of an excited surface wave in a domino plasmon configuration. This antenna has numerous applications as THz detectors and transmitters [16–20].

2. WAVEGUIDE BELOW A HOMOGENEOUS SUBSTRATE

It has been demonstrated in previous work that a periodic repetition of corrugations (as shown in the scheme of Fig. 1) produces a surface wave which has an upper cut-off frequency depending mainly on the height of the corrugations, h [4, 5]. This cut-off frequency is the lower limit of the region which is known as a "soft surface" in the Engineering Community [21]. Between the first and the second mode, the propagation perpendicular to the corrugations is not possible, and therefore, this region is typically employed to reject (or filter) the electromagnetic waves in a given band of frequencies [22, 23]. Contrary to this configuration, the same corrugations, when oriented in the perpendicular direction, enhance the propagation of quasi-TEM modes, and are known as "hard surfaces" [21, 24].

In Fig. 1, the propagation constant for the first two modes when corrugations are surrounded of vacuum is shown. The employed dimensions are $d = 0.2\,\text{mm}$, $a = 0.5d$ and $h = 0.8d$, assuming that the transversal length (L) of the dominos is infinite. In addition, it illustrates the light line for different permittivities of the materials.

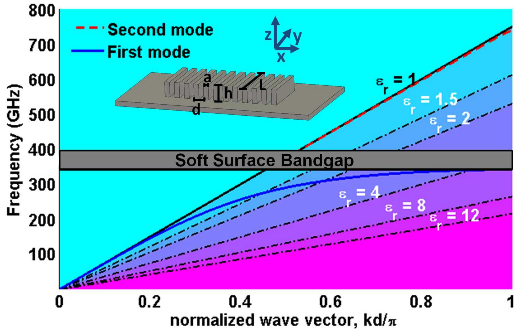

Figure 1. Propagation constant for $d = 0.2\,\text{mm}$, $a = 0.5d$ and $h = 0.8d$ and different light lines for different dielectric materials (from $\epsilon_r = 1.5$ to $\epsilon_r = 12$). Inset shows the description of the corrugated metallic configuration. Although the inset represents a particular example with few corrugations over a large ground plane, these results were obtained assuming periodic conditions of the corrugations in x and y axes.

The first mode of propagation, assuming an infinite case surrounded by vacuum, does not have any leaky loss (or radiation), in agreement with previous demonstrations [4, 5]. However, when an electrically dense material approaches the corrugations from above, since the propagation constant of the first mode is lower than the one of the dense material (as it is illustrated in Fig. 2(a)), it starts to operate as a leaky wave antenna whose main angle of elevation can be calculated by the following expression [13, 25]:

$$\gamma = \arccos(k_1/k_2) \tag{1}$$

where k_1 is the propagation constant of the surface wave and k_2 the light line for the dense material. For example, Fig. 2(c) illustrates the obtained angle of elevation for different dielectric material from $\epsilon_r = 1.5$ to $\epsilon_r = 15$ (for the propagation constant of the first mode represented previously in Fig. 1). As expected, the angle of elevation changes as the material properties of the slab are altered, but the main importance of these results resides in the fact that this angle is constant from very low frequencies until near to the cut-off frequency (where the propagation constant of the surface wave and the light line begin to diverge). These results are supported with multiple full wave simulations using *CST Microwave Studio* assuming an infinite dielectric medium in the positive z direction. The obtained results are also presented in Fig. 2(c) (with alternate crosses and circles) for the purpose of comparison purpose. In addition, in Fig. 2(b), the normalized radiation pattern obtained with the full wave simulations at 180 GHz with $\epsilon_r = 2$ is shown. These latter results were obtained for

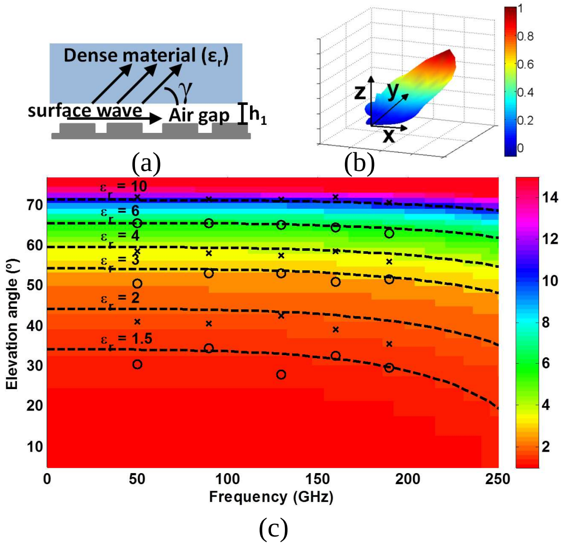

Figure 2. (a) Sketch of the antenna. (b) Radiation pattern (normalized directivity) with a frequency of 180 GHz and a dense material $\epsilon_r = 2$. (c) Angle of elevation of the main beam of the radiation pattern for different dielectric materials for $\epsilon_r = 1.1 - 15$ (particularly, $\epsilon_r = 1.5$, $\epsilon_r = 2$, $\epsilon_r = 3$, $\epsilon_r = 4$, $\epsilon_r = 6$, $\epsilon_r = 10$ in dashed lines). Alternate crosses and circles represent the angle of elevation obtained from full wave simulation for 100 corrugations along x axis.

a structure of 100 corrugations with a transversal length of $L = 20d$. As demonstrated in [4], the width of the corrugations has a very small impact on the propagation constant of the surface plasmon (which remains practically constant), therefore, the selection of this parameter is arbitrary. However, it is important to ensure that the number of corrugations is sufficient so that the reflections from the end of the structure are minimised and this will be defined by the amount of leaked (or radiated) energy. The separation between corrugations and the dense material was chosen to be $2h$. This separation (h_1) determines the amount of electromagnetic field leaked due to radiation. Fig. 3 illustrates the $|E|$ along the transmission direction when a dense material of $\epsilon_r = 3$ is placed at three different distances from the corrugations. According to these results, when the dense material is closer to the corrugations, the radiation is higher since the attenuation of the waves is stronger. However, if the distance between two media is too small, the radiation properties (i.e., the angle of elevation) would be degenerated since the propagation constant calculated for the corrugations in free space is no longer accurate.

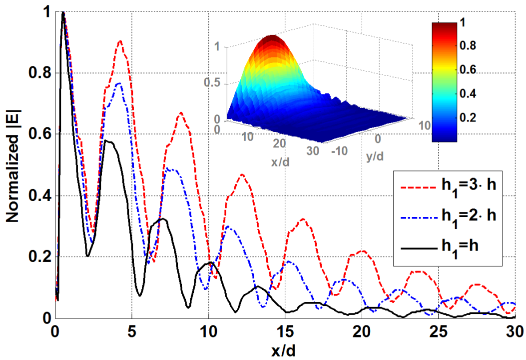

Figure 3. Normalized electric field distribution ($|E|$) along the corrugations ($z = 0.5 \cdot h$) at 180 GHz when a dense material of $\epsilon_r = 3$ is placed at different separations to the corrugations: $h_1 = h$, $h_1 = 2h$ and $h_1 = 3h$. Inset represents the normalized electric field distribution ($|E|$) in a 3D representation for the specific case of separation of $h_1 = h$.

Therefore, a compromise between the amount of energy radiated and the quality of radiation pattern must be found for the application under consideration.

Although these simulations were obtained using an infinite dielectric slab above the corrugations, in order to implement such an antenna, a termination of the dielectric slab is necessary. This termination should be normal to the direction of propagation of the leaky wave to avoid refractions; however some reflection will occur depending on the mismatch of the dielectric slab with respect to free space.

As a final note, although only one surface mode is studied in this paper, any other TM mode of this structure that exhibits a similar velocity to that of free space would also provide the same angle of radiation. However, this TM mode should be correctly matched to the surface mode propagating in the corrugations (based on domino plasmons) to avoid any reflection. An abrupt transition between a corrugated structure and a grounded metallic plate will produce reflections as illustrated in Fig. 4, reducing the radiating efficiency of the antenna.

3. WAVEGUIDE BELOW A GRADIENT INDEX SUBSTRATE

Since the elevation angle of the antenna is constant for a wide range of frequencies, the radiation pattern can be focused in a broadside

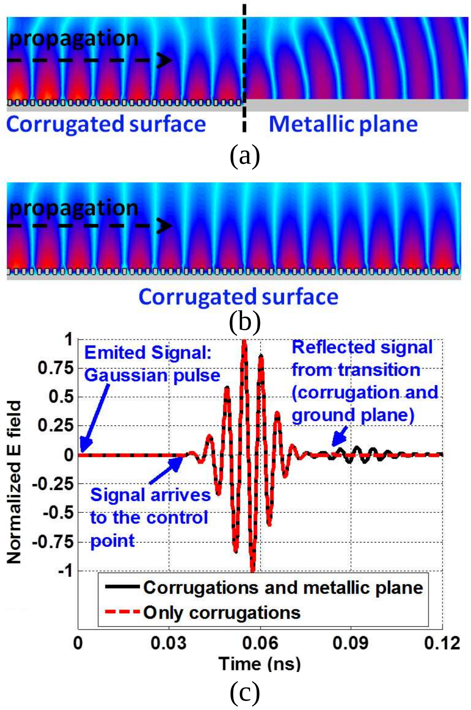

Figure 4. (a) Field distribution when the corrugated surface finishes with a metallic plane. (b) Field distribution when the corrugated surface has no transition. (c) Field distribution in the center of the corrugation, at a distance h above the corrugations and a distance $20d$ to the transition between corrugations and metallic plane. Solid black line refers to the structure in (a) and dashed red is for the structure given in (b). The simulation is performed for an incident Gaussian pulse.

direction with a lens on the top of the waveguide. In this paper, we propose the use of a GRIN lens whose dielectric permittivity fits the following expression:

$$\epsilon_r = b - a \cdot \left(\frac{x}{R}\right)^2 \tag{2}$$

where b is the maximum value of the dielectric constant, a a constant (in our case, it is equal to $b - 1$ to have $\epsilon_r = 1$ at $x = R$), x the longitudinal dimension, and R the size of the lens. The lens has been designed to have a maximum $\epsilon_r = 2$, therefore $b = 2$ and $a = 1$. In addition, it has been discretized in 10 dielectric slabs from $\epsilon_r = 1$ to $\epsilon_r = 2$ as Fig. 5(a) illustrates. This lens has been simulated with CST and the obtained normalized electric field is shown in Fig. 5(b). In

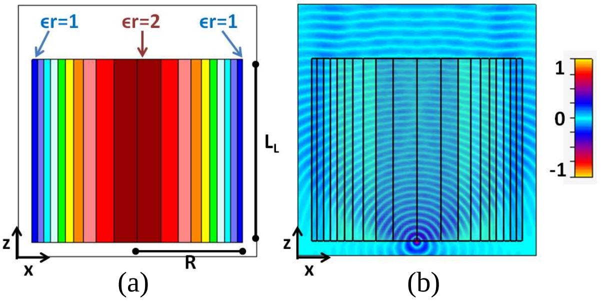

Figure 5. (a) Dielectric distribution of a GRIN lens discretized into 10 dielectric slabs following Equation (2) (with $b = 2$ and $a = 1$). The lens has a width of 19.6 mm ($2 \times R$) and a length of $L_L = 17$ mm. (b) Normalized electric field distribution in the GRIN lens after applying a normal electric source at the bottom at 170 GHz.

this example, a 2D parallel plate configuration (with thickness $\ll \lambda$) is studied, and it can be seen how a normal electric source excites a cylindrical wave which is transformed after the lens into a plane wave, i.e., focusing the fields in the broadside direction.

Therefore, this lens can be placed directly over the waveguide after an air gap (as shown in Fig. 6(a)) obtaining a broadside and very directive radiation. Fig. 6(c) shows the radiation pattern (in

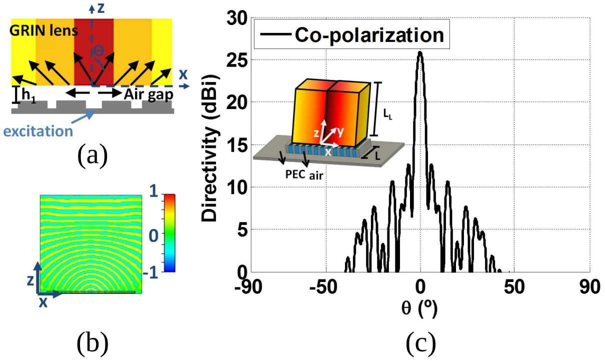

Figure 6. (a) Configuration: waveguide with GRIN lens on the top. (b) Electric field distribution for the combination of waveguide and GRIN lens at 180 GHz. (c) Radiation pattern at ϕ=0° (y=0) plane for the co-polarization of the waveguide with the GRIN lens on the top at 180 GHz.

terms of directivity) for the co-polarization in the $\phi = 0^\circ$ $(y = 0)$ plane (the plane along which the surface wave propagates). This result was obtained with a full wave simulation at 180 GHz, integrating both waveguide and GRIN lens, where the distance between the lens and corrugations is $2h$. The thicknesses of the lens slabs is constant and equal to L to allow all the energy that is distributed in the original waveguide to be radiated. Otherwise, the matching of the propagating mode and the radiation efficiency would be negatively affected. The height of the lens has been selected to 17 mm, in order to provide adequate focusing properties at 180 GHz. The Side Lobe Level (SLL) is low, -13.5 dB with respect to the maximum, and the cross-polarization in this plane is negligible, and with maximum in any direction being lower than -30 dB. Fig. 7 illustrates the directivity and SLL for the complete device from 120 GHz to 230 GHz (with two numerical methods: FDTD with *CST* software and FEM with *HFSS*), and the bandwidth of operation (i.e., SLL lower than -10 dB respect to the maximum) is 80 GHz (43%). The antenna was simulated considering a perfect matched port (centered at $x = 0$) to the surface wave, so there are no matching losses in the present design. However, although in theory a perfect matching can be achieved, losses in the dielectric slabs and the metallic corrugations ([4, 5]) will affect the properties of the antenna. Assuming metallic corrugations of gold and dielectric slabs of $\tan\delta = 0.001$; the simulated radiation efficiency at 180 GHz is 91%. The majority of the losses are associated with the dielectric slabs (8%), and the metallic corrugations produce approximately 1–2% (depending on the employed material: gold, silver and aluminium were studied).

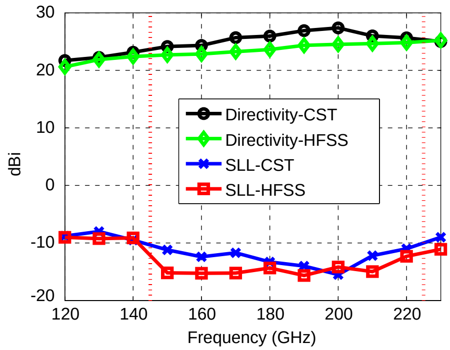

Figure 7. Directivity and SLL in the ϕ=0° $(y = 0)$ plane for the co-polarization of the whole antenna (including the GRIN lens) at different frequencies from 120 GHz to 230 GHz.

4. CONCLUSIONS

In this paper, it has been proposed a leaky wave antenna excited in a configuration including various dielectric slabs positioned above a spoof plasmon waveguide. The surface waves which propagate along the surface are gradually radiated due to the presence of a dense material. Since the propagation constant of the guided wave is similar to the light line for a very broad band, the angle of the elevation of the main beam of radiation is practically constant with frequency and depends only on the value of the permittivity of this dense material. This makes the antenna very attractive for practical applications since the shape of the radiation pattern is unchanged across a huge bandwidth of operation.

In addition, it has been shown the promising properties of a particular design of this antenna at 180 GHz and whose use for practical THz regime applications is feasible. For this purpose, an additional GRIN lens is proposed, which is able to transform the radiation pattern into broadside, with SLL lower than −15 dB and a cross polarization which is practically negligible.

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