ELECTROMAGNETIC MODELING OF DISTRIBUTED-SOURCE-EXCITATION OF COPLANAR WAVEGUIDES: APPLICATIONS TO TRAVELING-WAVE PHOTOMIXERS

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I. ABSTRACT

In this work an electromagnetic model and subsequent design is presented for a traveling-wave, coplanar waveguide (CPW) based source that will operate in the THz frequency regime. The RF driving current is a result of photoexcitation of a thin GaAs membrane using two frequency-offset lasers. The GaAs film is grown by molecular-beam-exitaxy (MBE) and displays sub-ps carrier lifetimes which enable the material conductivity to be modulated at a very high rate. The RF current flows between electrodes deposited on the GaAs membrane which are biased with a DC voltage source. The electrodes form a CPW and are terminated with a double slot antenna that couples the power to a quasi-optical system. The membrane is suspended above a metallic reflector to launch all radiation in one direction. The theoretical investigation and consequent design is performed in two steps. The first step consists of a direct evaluation of the magnetic current distribution on an infinitely extended coplanar waveguide excited by an impressed electric current distributed over a finite area. The result of the analysis is the difference between the incident angle of the laser beams and the length of the excited area that maximizes the RF power coupled to the CPW. The optimal values for both parameters are found as functions of the CPW and membrane dimensions as well as the dielectric constants of the layers. In the second step, a design is presented of a double slot antenna that matches the CPW characteristic impedance and gives good overall performance. The design is presently being implemented and measurements will soon be available.

II. INFINITELY EXTENDED CPW FED OVER A FINITE LENGTH ACTIVE REGION

An infinitely extended x-oriented CPW is considered (Fig. 1), which is etched on an infinite conducting plane between two multi-layered half spaces.
In the photomixer structure the active dielectric layer is a GaAs film, which is modeled as a dielectric homogeneous slab with relative permittivity $\varepsilon_{r2} = 12.9$. On top of the CPW ground plane there is a thin protective Si_3N_4 film ($\varepsilon_{r2} = 7.0$). The multi-layer structure has been subdivided in two regions. Region 1, $z > 0$, represents the protective layer (h_1, ε_{r1}), while region 2, $z < 0$, represents the active grounded slab (h_2, ε_{r2}), backed by an

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infinitely extended metallic reflector separated by a vacuum layer ($\varepsilon_{r0} = 1$) with a thickness of h_0. The cross section of both the arms of the CPW (slot "1" and "2") is uniform (w_S) and small in terms of the wavelength.

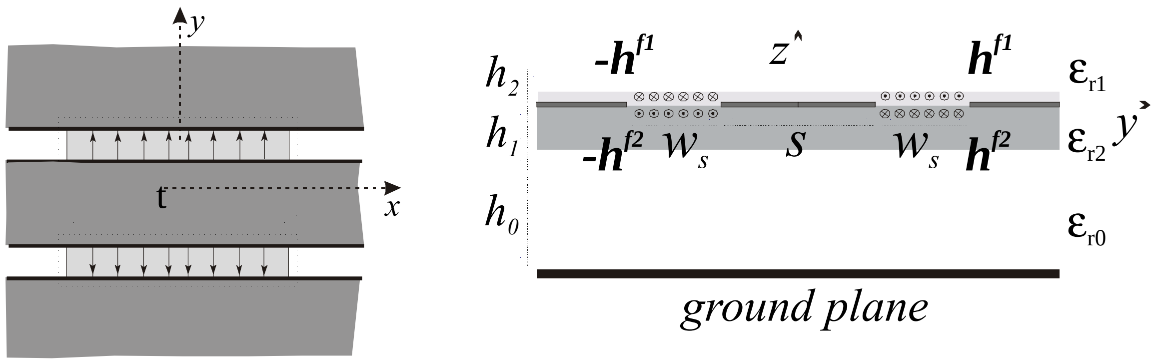


Fig. 1 Investigated geometry, top view and cross section

The separation between the internal edges of the slots is indicated as s. The induced RF currents $j_f\, \mathbf{i}_y$ may be interpreted by means of the equivalence principle as an x-oriented magnetic field discontinuity $(h^{f+} - h^{f-}) \cdot \hat{i}_x = h^f \cdot \hat{i}_x$, impressed at $z = 0^{\pm}$. The forcing magnetic fields are required to be equal and opposite in phase in slot "1" and slot "2" in order to be compatible with a propagating mode on the structure: $h^f(x, y) = -h^f(x, -y)$. Resorting to the equivalence principle the slotted regions are replaced by infinite, perfectly conducting surfaces with two unknown magnetic current distributions $\pm\boldsymbol{m}$ (immediatety above and below the CPW plane). These currents have equal amplitude and opposite signs, to ensure the continuity of the electric tangent fields through the CPW. Moreover, they are assumed x oriented due to the small cross sections of the two slots, i.e. $\pm\boldsymbol{m} = \pm m \cdot \hat{i}_x$. Thus, a scalar integral equation can be formulated which enforces the continuity of the total (impressed plus radiated) magnetic field on the CPW:

$$\int_{\Sigma_y}\int_{-\infty}^{+\infty} [g_{xx}(x - x'; y - y')] \cdot m(x, x')dx'dy' = -h^f(x, y), \tag{1}$$

where $\Sigma_y = [(-s/2 - w_s, -s/2) \cup (s/2, s/2 + w_s)]$ is the region of the slots; and $g_{xx}(x, y)$ is the sum of $g^1_{xx}(x, y)$ and $g^2_{xx}(x, y)$, the Green's functions pertinent to the lower and upper multi-layered half spaces, respectively. This integral equation is enforced on the two axis of the slots that compose the CPW by employing a point matching procedure – this is formally equivalent to weighting Eq. (1) over the transverse domain Σ_y with a two Dirac delta functions having opposite signs centered on $\pm a$. As anticipated, the magnetic current distribution dependence is separable in x and y, i.e. $m(x, y) = m_x(x) \cdot m_y(y)$. An edge singular behavior is assumed for the y dependence of the magnetic currents:

$$m_y(y) = \frac{2}{\pi w_s}\left[\frac{\mathrm{rect}(y+a, w_s/2)}{\sqrt{1-\left[\frac{2(y+a)}{w_s}\right]^2}} - \frac{\mathrm{rect}(y-a, w_s/2)}{\sqrt{1-\left[\frac{2(y-a)}{w_s}\right]^2}}\right], \tag{2}$$

where the $\mathrm{rect}(y,T)$ is the existence function equal to unity for $|y| \le T$ and zero elsewhere. The normalization of m_y is chosen to give unitary value when integrated on the transverse dimension of each of the slots. Moreover, the currents have opposite signs since a propagating mode is being excited on the CPW.

The integral equation can then be solved in the spectral domain and it is only dependent on the x variable. After a few algebraic manipulations it can be shown that the magnetic current distribution can be expressed as an inverse Fourier-transform:

$$m_x(k_x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} M_x(k_x)\, e^{-jk_x x}\, dk_x \tag{3}$$

with

$$M_x(k_x) = \frac{-2H_x^f(k_x)}{\frac{1}{2\pi}\int_{-\infty}^{+\infty} G_{xx}(k_x,k_y)\cdot J_0\left(k_y \frac{W_s}{2}\right)\cdot\left[-j2\sin(k_y a)\right]^2 dk_y}. \tag{4}$$

Equations (3)-(4) constitute the basic tools for the investigation of the distributed source characterization of the CPW that will follow in the next section. The integration path selection criteria for Eq. (3) and the properties of the singularities that arise from denominators in Eq. (4) are treated in detail in [1], [2] for a slot line printed between two different homogeneous dielectric half spaces. The integral in Eq. (3) can be performed by adopting a deformation in the complex plane below the real axis for $\mathrm{Re}(k_x) < 0$ and above the real axis for $\mathrm{Re}(k_x) > 0$.

III. DISTRIBUTED CURRENT SOURCE IN THE CPW: DESIGN CRITERIA

Equation 3 provides the framework to quantitatively determine the design parameters that optimize the coupling of power from the photo-induced current to the quasi-optical system. The reason for investigating distributed sources is the necessity to avoid the high laser densities required for operation of the small area photo-mixer devices. An active area with a length on the order of a few effective wavelengths would allow reducing the laser power density significantly below the damage threshold. Choosing an arbitrary length for the gain region may or may not guarantee preferential coupling to a forward traveling wave rather than to a backward traveling one. The backward traveling wave would render the design sensitive not only to the location of the CPW-antenna transition but also the opposite end where the DC bias leads attach. The following three guidelines were followed to obtain an optimal design:

a) The phase velocity of the impressed current distribution should match the group velocity of the quasi-TEM guided mode of the CPW.
b) The length of the active area in the extended CPW should guarantee that RF power is coupled only to the forward traveling wave.
c) The characteristic impedance of the CPW line should be matched to the antenna impedance.

III.1 Phase matching.

The CPW quasi-TEM guided mode propagation constant can be found by numerically investigating the dispersion equation $D(k_x)=0$. The search for a solution can be restricted to the real axis and the two poles of the structures, $\pm k_{xp}$ are found in the top Riemann sheet for $k_{zi}=\sqrt{k_i^2-k_x^2-k_y^2}$, $i=0,1$ and 2.

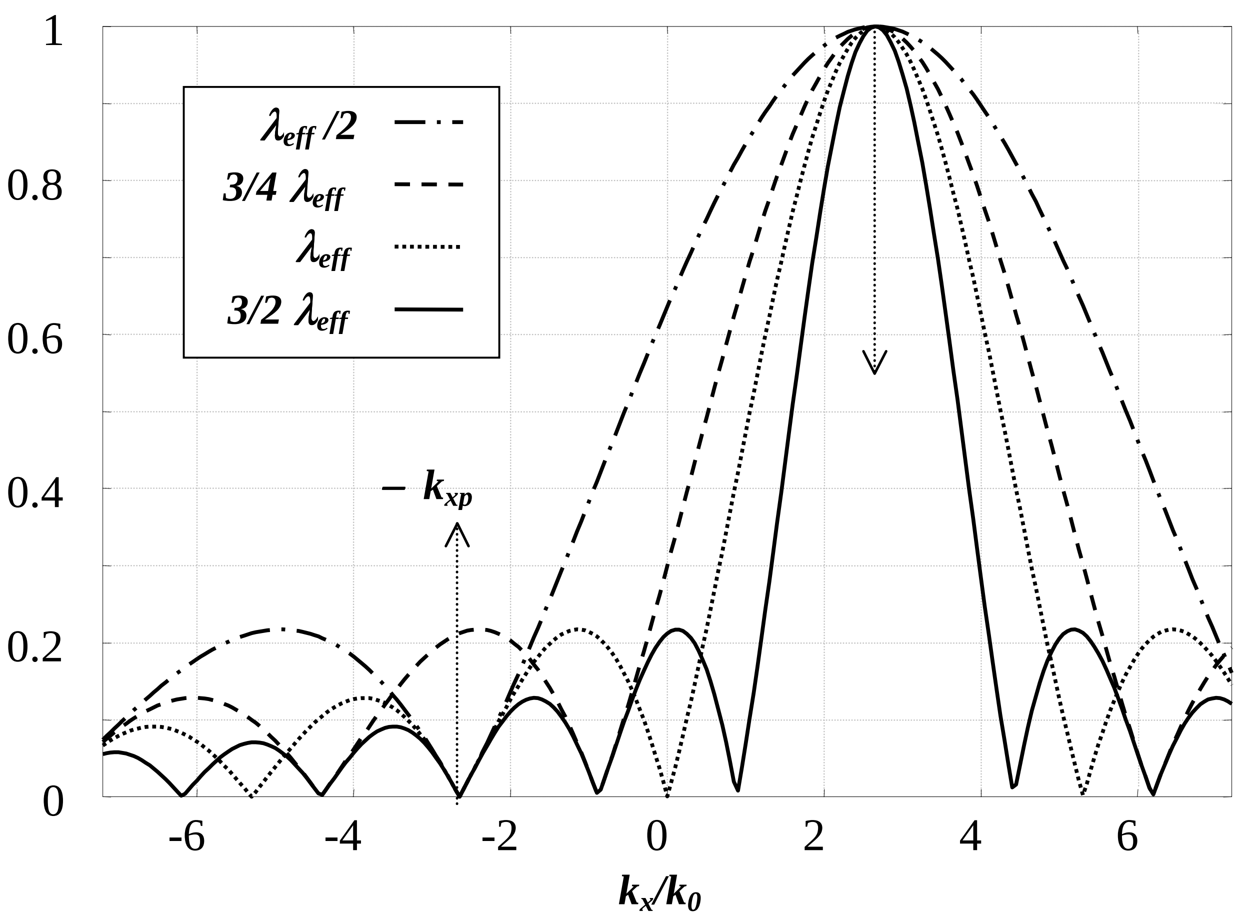


Fig. 2 Fourier transform of the impressed magnetic field for distributed excitations over different active area lengths

Thus, possible branch point singularities and branch cuts in the k_x-plane, arising from the fact that $D(k_x)$ is a multi-valued function [2], are avoided when the attention is restricted to the main quasi-TEM mode. Once k_{xp} is known we verified numerically the well known principle that an impressed RF current tends to couple to the CPW when the phase velocity of the current (k_{x0}) matches the intrinsic quasi-TEM propagation constant of the structure, i.e. $k_{x0} = k_{xp}$.

III.2 Optimal length of the active area.

The second key design parameter can be extracted from the analysis is the optimal extension of the active area. Figure 2 shows the Fourier transforms of the impressed magnetic fields when distributed on different active area lengths of the CPW. In all cases the Fourier transforms are sinc functions where the maximum corresponds to $k_x = k_{xp}$. It should be noted that when the dimension of the active area is an integer multiple of half the effective wavelength the spectrum of the distribution is equal to zero in

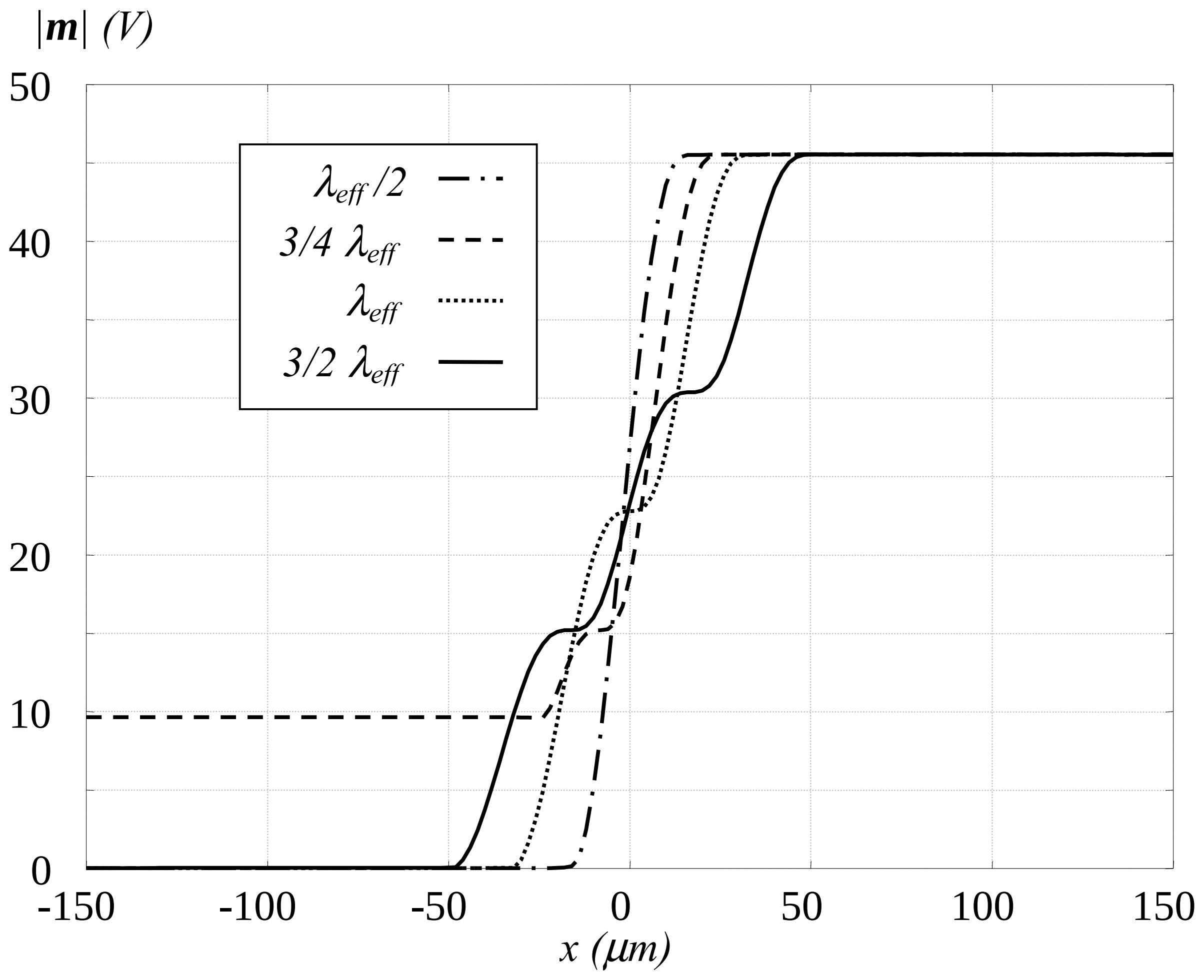


Fig. 3 Magnetic current amplitude on CPW line at the end point of an excitation region indicated in the inset

$k_x = -k_{xp}$. Since the integration in Eq. (6) is widely dominated by pole contributions on the real axis, a zero in $k_x = -k_{xp}$ provides a zero-pole cancellation such that no power is coupled to the backward traveling wave. For gap excitations over small areas, the power would be equally distributed in the forward and the backward propagating traveling wave.

This is shown in **Fig 3** where the magnetic current distributions are shown as a function of x for the same total forcing field (impinging laser power). The selected CPW is characterized by h_2 = 2.25 μm, ε_{r2} = 12.9, h_1 = 0.1 μm, ε_{r1} = 7.0, h_0 = 35.0 μm , w_s = 0.7 μm, s = 1.5 μm. It is worth noting that for an active area of $3/4\,\lambda_{\mathrm{eff}}$ a significant fraction of the power is also launched backward.

III.3 Impedance matching antenna-CPW.

The asymptotic value of the magnetic current amplitude at large distance from the active area, when the phase velocity of the impressed field matches the phase velocity of the quasi TEM mode in the CPW is the characteristic impedance of the line. Two considerations determined the transverse geometrical dimensions of the CPW:

a) The characteristic impedance needs to be as low as possible since it is difficult to achieve a high impedance with slots operating on the second resonance in the given dielectric configuration.
b) The width of the CPW inner conductor should be small in order to minimize the laser power reflected from the metal.

A value of 45 Ω has been set as target for the characteristic impedance. Taking into account that the fabrication tolerance is on the order of 0.1 μm a width of >0.5 μm seemed feasible. In order to achieve such an impedance level a double slot antenna configuration has been chosen. The slots are series fed by the optically pumped CPW, and they are separated by one effective wavelength (λ_{eff}) in order to obtain the mandatory broadside radiation requirement that is guaranteed by equal magnetic currents in the two slots. The slots are designed to present purely real active impedance (the impedance of each slot when also the other are excited) at the design frequency. So the λ_{eff} separation guarantees, by simple transmission line considerations, that the eventual input impedance of the entire antenna system is the sum of these active impedance's.

IV. DOUBLE SLOT DESIGN *(1.7 THz)*

Two slots of length 90μm and width 12 μm are sufficient to provide about 45 ohms of input impedance. The slots are separated by a distance equal to 64 μm. The stratification is the same used for fig. 5. The reflection coefficient in the band 1.6 THz to 1.9 THz is shown in Fig. 4. It shows a match better than 20 dB at a central frequency of 1.77 THz and 6% relative bandwidth at –10 dB. The normalized magnetic currents in the two different slots are shown to be equal in Fig. 5, where the real and imaginary part of the currents at the frequency of 1750 GHz are superimposed. The separation between the two slots ($\lambda_{eff} \cong 0.38\ \lambda_0$) represents a slightly over-sampled array and this causes a non

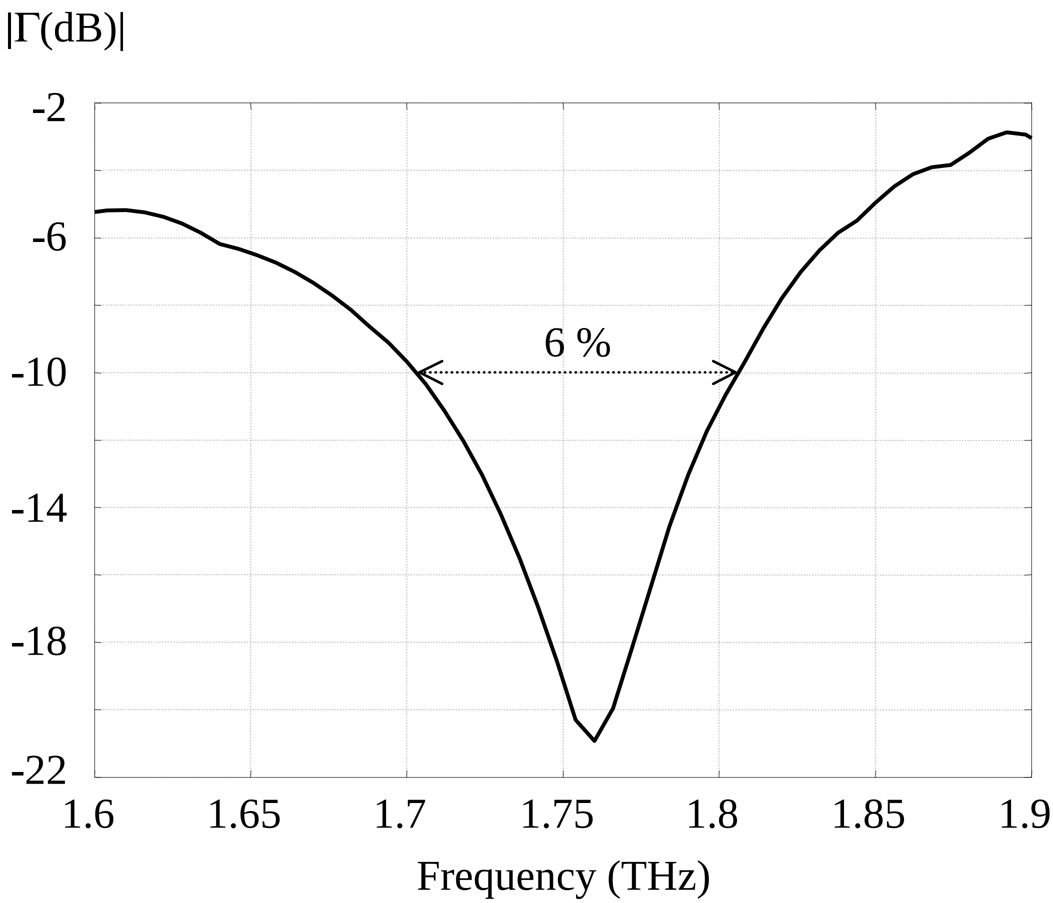


Fig. 4 Reflection Coefficient for a double slot antenna

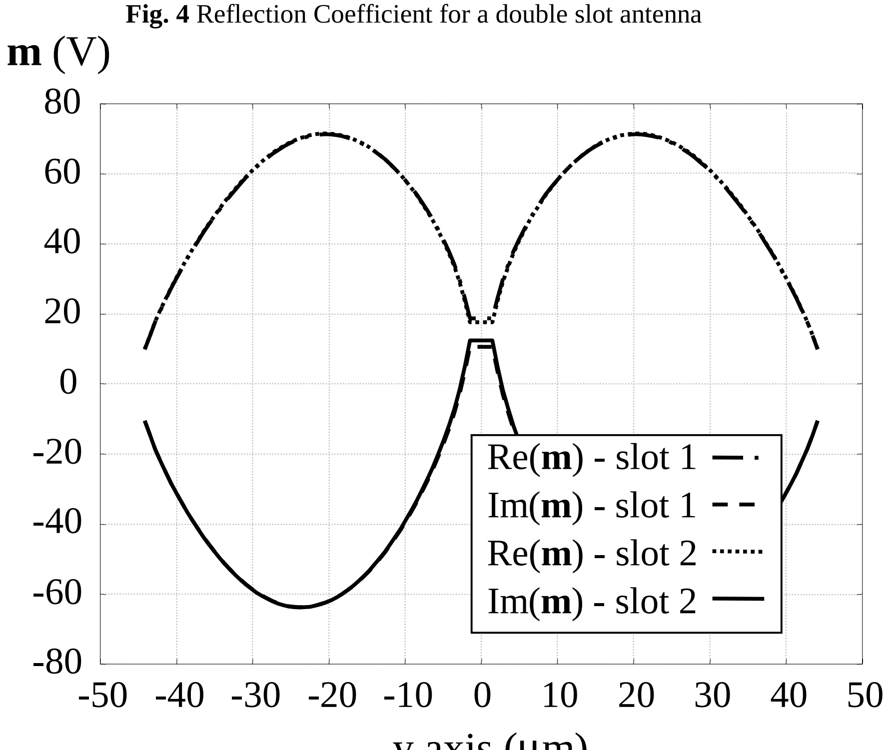
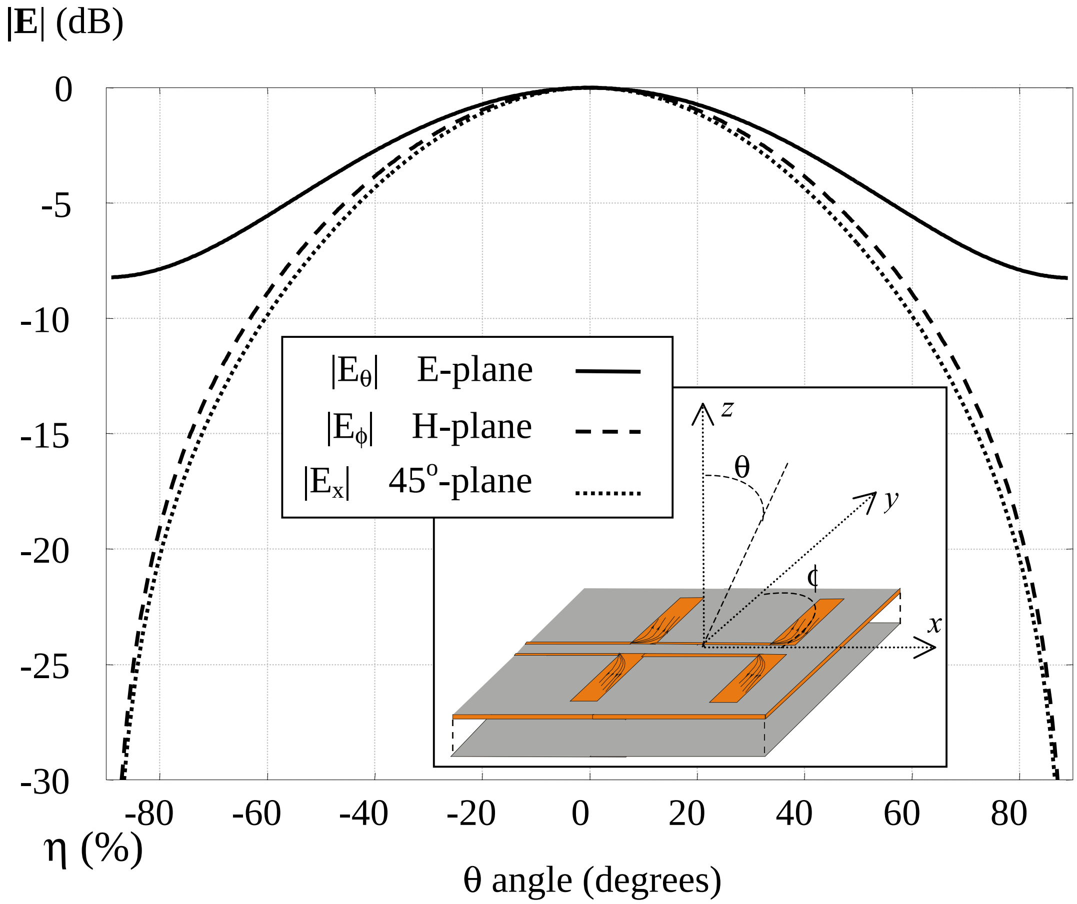


Fig. 5 Magnetic currents in the two slots of the array (f = 1.750 THz)



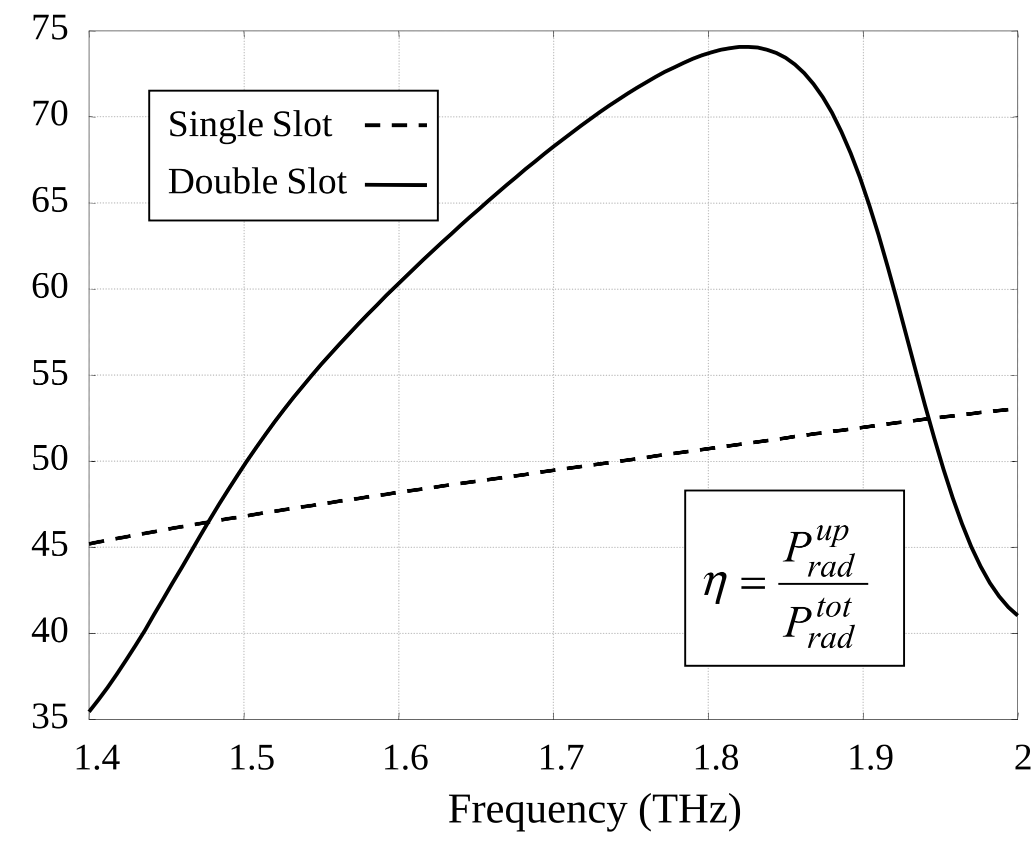


Fig. 6 (a) Copolar radiation pattern of double slot array antenna. (b) Radiation efficiency: comparison between the double slot array and a single slot perfectly rotationally symmetric pattern, as in Fig. 6a where the copolar radiation pattern of double slot array antennais shown. E_θ field in E-plane (continuous line); E_ϕ field in H-plane (dashed line); E_x field in diagonal plane (dotted line). On the other hand, with this separation a good efficiency (η), intended as the ratio of the power radiated in free space and the power lost in the parallel plate wave-guide mode is obtained (Fig 4b). The efficiency is significantly better than the one of the single slot antenna, also reported in Fig. 6b, thanks to the cancellation of the waves launched in the inhomogeneous PPW by the two slots.

VI. CONCLUSIVE CONSIDERATIONS

A travelling wave, CPW based designs of optically pumped LO's for 1.7 THz frequencies has been presented. The designs are based on separate steps to optimize first the coupling from the R.F. currents photo-induced to a forward traveling wave on the CPW, and then the coupling from the CPW to free space by means of double slot antenna. The theoretical aspects of the distributed source excitations of CPW on thin membranes. The validity of the design considerations presented has been verified by means of full wave MoM simulations of the entire structure. The designs are at the present time being manufactured and the results achieved will be the object of a future publication.

Reference

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[2] Mesa, F.; di Nallo, C.; Jackson, D.R. "The theory of surface-wave and space-wave leaky-mode excitation on microstrip lines" on IEEE Transactions on Microwave Theory and Techniques, Volume: 47 Issue: 2 , Page(s): 207 -215, Feb. 1999