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Dual-Layer Frequency-Selective Grid Polarizers on Thin-Film Substrates for THz Applications

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***Abstract*— Dual-layer frequency-selective subwavelength grid polarizers on thin-film dielectric substrates are proposed for THz and sub-THz applications. The dual-layer grids possess enhanced (squared) polarizing efficiency at a sequence of discrete frequencies in reflection and within extended frequency bands in transmission as compared to conventional single grids.**

I. Introduction

This work is concerned with development of enhanced dual-layer grid polarizers of record-breaking performance in THz and sub-THz bands as compared to conventional grids.

Enhanced THz polarizers are needed in astrophysics (detection of polarization of Cosmic Microwave Background at the level about $-80dB$), polarization interferometry (space-borne defence-related systems), polarimetric remote sensing and security checks (target detection and recognition), spectroscopy (atmospheric research, chemical and pharmaceutical industry) and other areas.

Conventional grid polarizers dominated the area for many decades [1], [2]. For today, however, this design has nearly exhausted its potential. Now, more advanced structures are needed, e.g., those based on chemically etched vertical or horizontal microstrip grids produced by special techniques (photolithography etc [2]), designed for exceptional performance in specific frequency bands, manufactured with extremely fine grids for THz and infrared systems, and optimized for particular applications [3].

Despite the availability of advanced technologies, manufacturing high-quality THz band polarizers is a complicated problem. Ideally, the finer grid, the better is the polarizer. In practice, finite conductivity of wires and irregularities of grids impose limitations, which become more restrictive for finer grids at the higher operation frequencies. Eventually, finite conductivity of microstrips or metal wires sets an absolute upper limit on the efficiency of THz polarizers when extremely thin wires or metal strips are used in these devices.

A possible way of relaxing the limitations is the use of multi-layer grid structures (photonic devices) of subwavelength period of each grid, though of resonant inter-layer spacing. The latter should improve the polarizer performance and increase the efficiency in THz band when using relatively coarse grids of thick wires, which are less expensive and much easier to produce and operate.

Though multigrid structures have been studied for many applications [4], [5], there is only one report published recently that suggests a possibility of multiplication of extinction ratio of two polarizers in tandem [6]. In that instance, however, the authors based their conclusions on Mueller matrices of abstract polarizers that do not account for the correct self-consistent solution of the electromagnetic problem and, as a result, missed a range of frequency-selective properties (the fact that the extinction ratio increases at certain frequencies while decreases at others, the dependence of the effect on transmission or reflection mode of operation, etc).

Computer simulations made recently for special dual-layer grids [7] (Fig. 1) predict a resonant growth of polarization extinction ratio (up to $80dB$ instead of the initial $40dB$ for some realistic design, in line with proposition [6]) which is expected in certain frequency bands or at particular frequencies, depending on the choice of either transmission or reflection mode of operation (a notion of strong frequency effects has been missed in [6]).

The aim of this work is to develop a practical design and undertake experimental manufacturing of a few sets of polarizer-analyzer pairs of dual-layer microstrip-grid THz polarizers with subsequent experimental testing of their polarizing efficiency. The sets would include both the ultra-fine grids for ultimate high-frequency electromagnetic performance and relatively coarse model structures for detailed measurements of their polarization characteristics.

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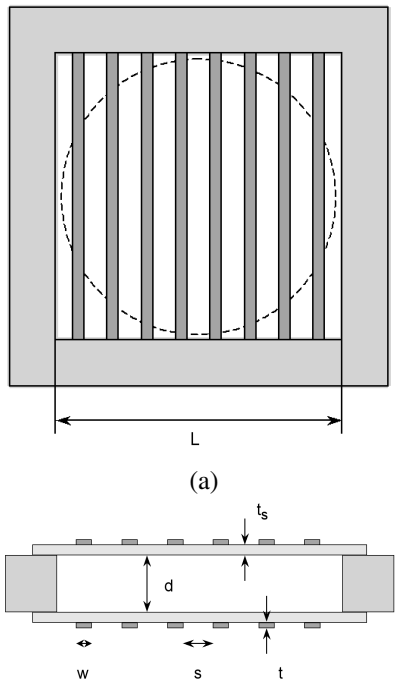


Fig. 1. Schematics of a dual-layer polarizer

TABLE I
GRATING PARAMETERS

Grating #	**Strip Width** $w,\ \mu m$	**Slot Width** $s,\ \mu m$	**Period** $p,\ \mu m$	**Spacing** $d,\ \mu m$
1	6	14	20	500
2	80	120	200	700

II. SIMULATIONS

Developing THz polarizers is a challenging issue because of constrained manufacturing requirements (Table I), significant absorption losses in common materials, lack of powerful radiation sources, limited capabilities of detectors, etc. Therefore, detailed computer simulations are needed for proposing an optimal design.

A. Approximate Asymptotic Model

An asymptotic model is based on effective boundary conditions for subwavelength grids obtained by L. A. Wainshtein. The conditions relate the averaged (smoothed) values of the electric and magnetic fields on the opposite sides of a subwavelength grid for both polarizations of the incident wave. By using the boundary conditions, one can evaluate, as a self-consistent electromagnetic solution, both the transmission and reflection coefficients of a composite structure made of a few layers of grids of any orientation and a few layers of any dielectric (e.g., ferrite) materials, for any polarization and inclination of the incident electromagnetic wave.

The approach is implemented in the computer software [7] in such a form that one can easily combine any kinds of layers in any order and compute the entire structure performance

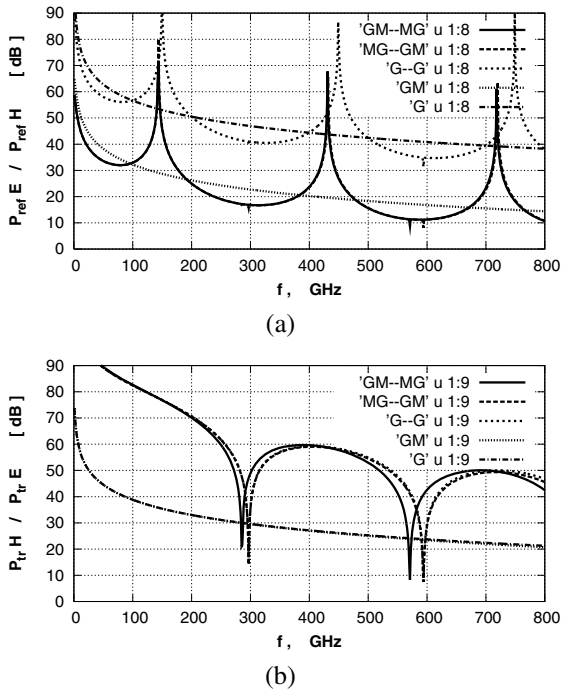


Fig. 2. Extinction ratio in reflected and transmitted waves for polarizers of gratings #1 on Mylar substrates when gratings are made on either the outer (GM-MG) or the inner (MG-GM) faces as compared to free-standing dual-layer (G-G) and single-layer (GM and G) grid polarizers

(e.g., the efficiency of a stack of layers as a Bragg mirror polarizer) by direct multiplication of relevant matrices, with a possibility of automatic optimization of the whole structure with respect to the given parameters.

B. Exact Simulations Based on Regularization Methods

A rigorous approach is developed for microstrip gratings on dielectric substrates by using regularization methods with account of absorption in gratings and substrates [7]. Computer simulations for copper gratings of Table I on $12\mu m$ Mylar films confirmed superiority of dual-layer grid polarizers over single grids of realistic design (Figs. 2 – 6).

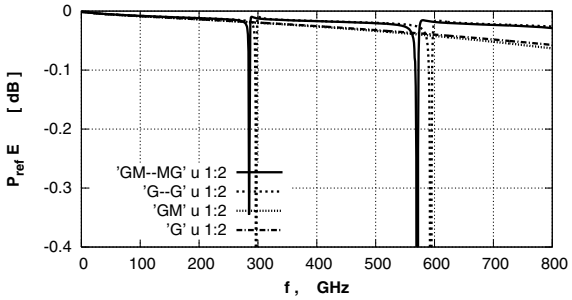
Computer simulations reveal the following effects:

(a) a significant (quadratic) growth of polarization ratio in reflected waves (the ratio $R_{ref} = E_{ref}/H_{ref}$ of reflected amplitudes for the incident E (co) and H (cross) polarized waves when either E or H is parallel to metal strips) that happens at certain "spike" frequencies f_n (Fig.2, a)

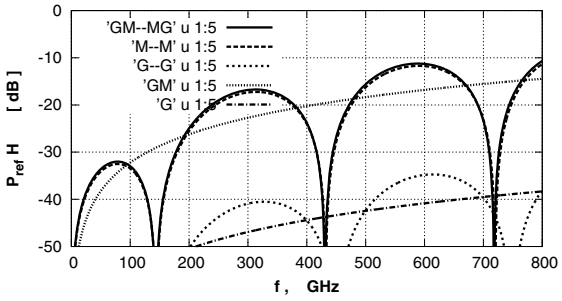
(b) a similar growth of polarization ratio in transmitted waves (the ratio $R_{tr} = H_{tr}/E_{tr}$ of transmitted amplitudes for the incident H (cross) and E (co) polarized waves) that occurs in extended frequency bands centered around the "spike" frequencies f_n (frequency-selective operation due to the resonant effects (Fig.2, b),

(c) a precise $3dB$ splitting of the incident non-polarized beam into reflected and transmitted polarized waves that occurs at the "spike" frequencies f_n regardless of the design parameters of separate grids (Fig.5).

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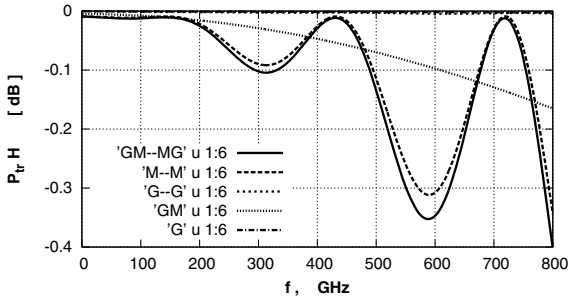


(a)

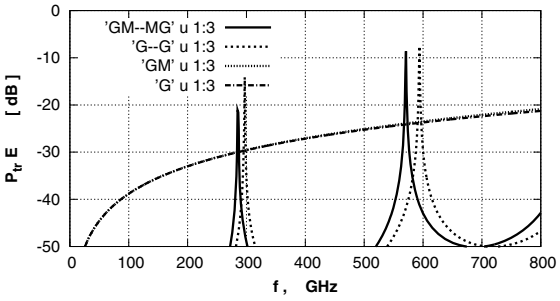


(b)

Fig. 3. Reflected power in (a) co- and (b) cross-polarization (E and H waves, respectively) that explains the spikes of enhanced polarization in Fig.2, a



(a)



(b)

Fig. 4. Transmitted power in (a) cross- and (b) co-polarization (H and E waves, respectively) that explains broad bands of enhanced polarization in Fig.2, b

Figs. 3 – 4 explain the enhancement of dual-layer grid polarizers by showing the frequency dependence of reflected and transmitted power of co- and cross-polarized waves. The reason of enhancement is the suppression of (small) reflected cross-polarized component (H wave, with E field orthogonal to strips) and transmitted co-component (E wave, with E field parallel to strips) that occurs due to destructive interference of relevant waves. This happens when the inter-grid spacing $d = (2n-1)\lambda/4$ where λ is the radiation wavelength ($n = 1, 2, 3, \ldots$). This is precisely the condition of "spike" frequencies f_n. Meanwhile, conventional half-wavelength resonant frequencies ($d = n\lambda/2$) correspond to dips of polarizing efficiency due to increased transparency of dual-layer grids for co-polarized waves (Fig. 3, a).

C. Specific Features of Polarizers on Thin-Film Substrates

Thin-film substrates of low-loss dielectrics do not substantially affect the polarizer performance in transmission mode. In reflection, however, they produce non-polarized waves that may substantially degrade the device (Fig. 2, a).

Despite this negative effect (which is small for thin substrates) the enhanced polarizing performance in reflection at the "spike" frequencies f_n is, typically, higher for dual-layer grids on film substrates as compared to similar single-layer grids suspended in free space.

Thus, by using grids of period p and strip width w so that cross-polarized reflectance is reduced versus co-polarized transparency in free-space while being comparable on substrates, one can increase the polarizing efficiency of dual-layer grids on substrates at "spike" frequencies in both reflection and transmission (if a beam splitters is needed) and within extended bands in transmission. This is the condition satisfied by gratings #1 (Table I).

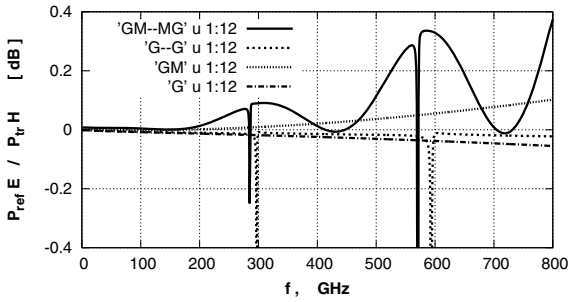


Fig. 5. Polarizer as a $3dB$ power splitter

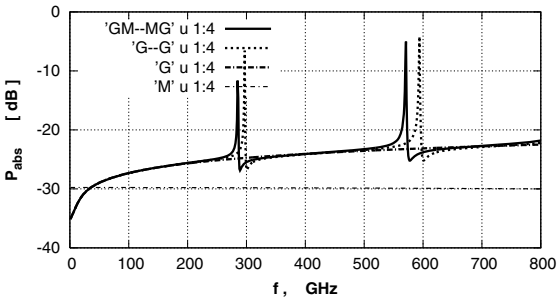


Fig. 6. Power absorbed by a dual-layer polarizer

An interesting feature of a dual-grid polarizer is an exact half-power splitting of a non-polarized beam into reflected

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and transmitted polarized waves that occurs at the "spike" frequencies regardless of the grid parameters. For a coarse-grid dual-layer polarizer, exact half-power splitting occurs at the "spike" frequencies only (Fig. 5) whereas for fine-grid structures it remains accurate within the entire bands of enhanced polarized transmission.

Another feature typical for all resonant structures is a rapid increase of absorption at the resonant frequencies (Fig. 6), though it is of minimal importance for these devices since it happens at the dips of their polarizing performance.

III. Experimental Issues

A. Manufacturing Requirements

A few sets of THz grid polarizers are currently being manufactured at the Tyndall National Institute facilities (Cork, Ireland). Each polarizer is made as an assembly of two parallel gratings attached to a frame of appropriate aperture and thickness.

A practical design is an assembly of a pair of microstrip gratings made of copper-clad polyimide films (of minimal standard $12\mu m$ thick polyimide and $2\mu m$ copper). The films are stretched on the opposite sides of a square frame with an aperture opening $L = 70mm$, spaced $d = 0.5mm$ apart due to the frame thickness (optimal for $f = 150GHz$ applications), and processed to obtain gratings on both films that should be perfectly aligned for their optimal performance (Fig. 1).

Two types of gratings are being produced as specified in Table I. Gratings #1 are defined by the strip width $w = 6\mu m$, the slot width $s = 14\mu m$, and the grid period $p = 20\mu m$ to achieve maximum performance in transmission mode at relatively high frequencies ($f = 150GHz$ at the lower end, if defined by the frame thickness $d = 0.5mm$). Gratings #2 are specified by $w = 80\mu m$, $s = 120\mu m$, and $p = 200\mu m$ to make them suitable for electromagnetic testing at a lower frequency ($f = 100GHz$, if $d = 0.7mm$).

The gratings in each assembly should be sufficiently planar and parallel, with non-planarity and non-parallelism of grating planes less than $7\mu m$ over the aperture area. Misalignment of strip directions of two gratings should be better than 20 arcseconds that corresponds to misfit of strips of different grids by about $w = 6\mu m$ (about one strip width of #1 gratings) at one end of the grid pair as compared to the other end (assuming the strip length $L = 60mm$).

B. Requirements for Electromagnetic Testing

A pair of dual-layer grid assemblies that constitutes one polarizer-analyzer set is needed for polarization experiments. Polarizers of one set (coarse gratings #2) are going to be tested for their electromagnetic performance at relatively low frequencies of $f = 100 - 300GHz$. The other set (fine gratings #1) will be used at the higher frequencies (potentially, exceeding the frequency $f = 500GHz$).

Requirements for high-frequency testing of enhanced polarizers are demanding. In addition to precise positioning of polarizers in cross-orientation with an accuracy better than 10 arcminutes for maintaining spurious signals below $-50dB$ (similarly, 1 arcminute for $-70dB$), detection of signals of ultra-low level is needed. As a promising way of solving the problem, one may use a resonator technique being developed for electromagnetic testing of low-loss structures [8].

When expressing electromagnetic properties of a subwavelength grid in terms of homogenized parameters, one can find the effective permittivity of grid in co-polarization to resemble the permittivity of plasma below the plasma frequency. Then, by measuring the effective permittivity of a dual-layer grid, one can verify the electromagnetic parameters of polarizer against numerical simulations.

An alternative representation of the same data is the plot of complex scattering matrix coefficients S_{11}, S_{12} that shows specific features of resonant behaviour of dual-layer polarizers, thus providing both the qualitative and quantitative characterization of these devices.

IV. Conclusions

In summary, dual-layer grid polarizers have the following advantages as compared to conventional grids: (a) a significant increase of efficiency, even in the case of coarse grids of thick wires, (b) an increase of the absolute upper limit of efficiency achievable with fine grids, (c) frequency-selective performance in either broad or narrow bands, and (d) a possibility of tuning the operation bands by varying the device inter-layer spacing or tilting the polarizer with respect to the incident wave.

Further development may require the fabrication of dual-layer grids on rigid substrates (assuming sufficiently low losses) for the better control of tolerances as necessary for pushing the operating frequencies higher into the THz band.

Acknowledgment

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