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► **To cite this version:**

Jean-Paul Guillet, Ronan Adam, Annick Pénarier, Jeremie Torres, Philippe Nouvel, et al.. A new THz passive radial polarizer. 33rd International Conference on Infrared, Millimeter and Terahertz Waves, 2008, Pasadena, United States. 10.1109/ICIMW.2008.4665608 . hal-01904190

**HAL Id: hal-01904190**

**<https://hal.science/hal-01904190v1>**

Submitted on 16 Jul 2021

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# A New THz Passive Radial Polarizer

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**Abstract**—A new THz radial polarizer suitable to convert the usual linearly polarized signal from a millimeter or sub-millimeter source is described. It is based on mode-filtering within a cylindrical waveguide combined with two tapers and a discontinuous phase element. An experimental demonstration is given at  $\approx 100$  GHz and transposition to higher THz frequencies by scaling is straightforward.

## I. INTRODUCTION

As experienced in the optical domain, the generation and use of radially polarized beams should have a significant impact in the evolution of the THz community, especially in the near-field microscopy and derived techniques as well as in THz plasmonics. At optical frequencies, the management of symmetric fields has strongly improved high numerical aperture focusing [1] and near-field optical microscopy and plasmonics [2]. All these studies take benefit from the total field symmetry provided by radial polarization, thereby leading, for example, to focused fields with either a strong longitudinal component [1], [3] or a p-polarization state with symmetry of revolution. So far, only a very limited number of systems allow the generation of radially polarized THz beams. All of them are based on the excitation of the mode sustained by metal wires whose electric field distribution is radial around the wire [4].

We propose in this communication a new concept of passive radial polarizer at THz frequencies. Such a system is aimed at working with continuous waves and it is specially designed for radiating in free space a radially polarized doughnut mode. It has the advantage to be simple and adaptable to any kind of existing THz continuous sources. The principle proposed here is directly derived from the concept of an optical radial polarizer [5].

## II. POLARIZER DESIGN

The TEM mode of a coaxial waveguide is in essence radially polarized. However, coaxial waveguides are challenging to built at THz frequencies and the radiation efficiency of the wire mode in free space is questionable [4]. We consider here a hollow circular waveguide because its  $TM_{01}$  mode is also radially polarized although it is a high-order mode. Our polarizer design thus rely on the adequate rejection of the fundamental linearly polarized  $TE_{11}$  mode whose cut-off frequency is lower than that of the desired  $TM_{01}$  mode. The difficulty with free space propagation is then to couple and decouple efficiently with guided modes.

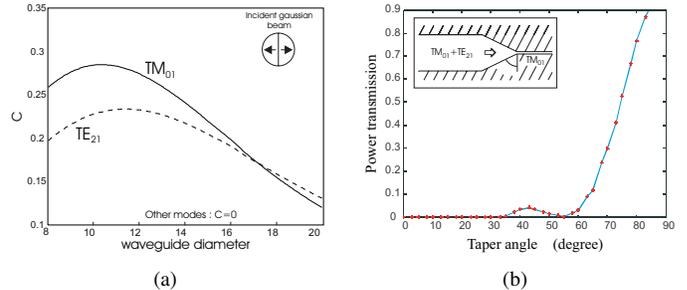


Fig. 1. (a) Coupling efficiency  $C$  between a Gaussian beam and the various modes sustained by a cylindrical hollow waveguide of perfect metal, as a function of the waveguide diameter. Half the incoming Gaussian beam cross-section has been phase retarded by  $\pi$  using a discontinuous phase element (see inset). (b) Channeling efficiency of the  $TM_{01}$  mode as a function of the taper angle  $\theta$ . The diameters of the large and small waveguides are  $7\lambda$  and  $0.9\lambda$ , respectively.

The coupling efficiency between the waveguide modes and an incoming Gaussian beam has been calculated to optimize the power conversion efficiency [6]. Results given in Fig. 1(a) show the calculated coupling efficiency in the two propagating modes  $TM_{01}$  and  $TE_{21}$  as a function of the circular input waveguide radius. A linearly polarized input beam fed through a discontinuous phase element is considered as input. An optimum of  $\approx 30\%$  appears at a radius of  $\approx 10\lambda$ . Next, a taper is used to reduce the waveguide to a dimension small enough so that only the  $TM_{01}$  mode can propagate. The Fig. 1(b) help us to chose the taper angle  $\theta$ : provided that  $\theta \geq 83^\circ$  a quasi adiabatic regime is reached and more than 90% of the input  $TM_{01}$  mode energy is transferred to the smallest guide.

## III. POLARIZER REALIZATION & RESULTS

The experimental realization of the radial polarizer was conducted at  $\approx 100$  GHz and the overall experimental arrangement is given in Fig. 2. At the heart of the polarizer is a hollow circular waveguide of 2.7 mm diameter that supports the simultaneous propagation of both the  $TE_{11}$  and  $TM_{01}$  modes. Input is tapered with a circular horn up to an external aperture of diameter  $\approx 20$  mm. Adiabatic conversion of the free-space propagating mode is ensured by a taper angle less than  $10^\circ$  with a resulting attenuation  $\leq 0.5$  dB. For convenience, the output of the waveguide is also tapered but to a limited diameter of  $\approx 5$  mm well adapted to the near-field probing of the output employed as detection.

Mode selection in the circular waveguide is obtained by

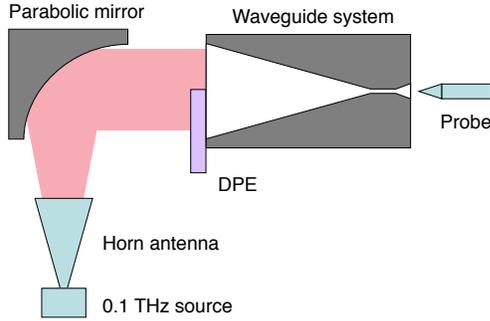


Fig. 2. Scheme of the experimental setup.

help of a halfwave PTFE plate inserted before the input taper. The plate position can be adjusted manually to cover only half of the taper geometrical acceptance and then creates a null field at center that favors only the  $TM_{01}$  mode in the circular waveguide. Owing to large enough propagation length of a few wavelengths in the circular waveguide, the output field includes only the  $TM_{01}$  mode with the desired radial polarization.

The polarizer has been realized by micromachining an aluminium rod. Transmission experiments were conducted using an electronic source emitting in free space. Detection involved a Schottky diode coupled to a PTFE pyramidal probe tip of principle similar to Ref. [7]. Detection is thus linearly polarized depending of the probe orientation. Probe position is kept close to the  $\approx 5$  mm diameter polarizer output. Images obtained when the axis of the polarizing probe stage is set parallel and perpendicular to the incoming polarization direction are displayed in Figs. 3(a) and 3(b), respectively. These orientations are indicated by white arrows on each image. A numerical reconstruction of the outgoing beam from Figs. 3(a) and 3(b) is provided in Fig. 3(c).

Two-grain structures jump out in Figs. 3(a) and 3(b). As expected, their directions follow the prescribed axis of the polarizing micro-detection system. The numerical combination of these two orthogonal patterns leads to an annular shape intensity distribution. The null intensity at the beam center evidences that the fundamental  $TE_{11}$  mode, whose maximum is expected at the center, has been totally rejected by the structure. Moreover, the visibility of the two-spots pattern remains unchanged when the probe axis is rotated (Figs. 3(a) and 3(b)). This is another evidence that all higher modes, except  $TM_{01}$ , are reflected by the system. These observations validate our concept of THz radial polarizer. Note that the efficiency of this prototype cannot be measured with precision by means of the uncalibrated detection tools that we used.

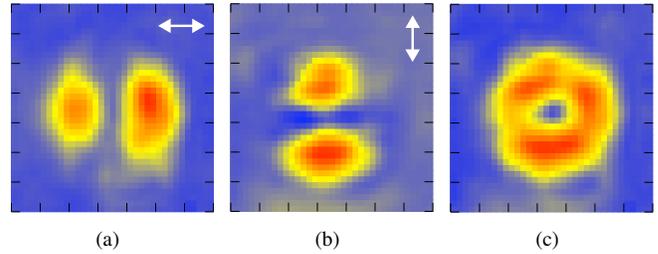


Fig. 3. Acquisition results of the field distribution transmitted by the prototype over a scan of  $7 \times 7$  mm<sup>2</sup>. (a) and (b) are images acquired for two orthogonal axis of the polarizing detection probe (axis indicated by arrows). (c) Numerical combination of (a) and (b).

#### IV. CONCLUSION

A new THz radial polarizer suitable to convert the usual linearly polarized signal from a millimeter or sub-millimeter source is described and demonstrated at  $\approx 100$  GHz. Its principle of operation involves an adequate mode filtering in a metallic cylindrical waveguide that supports only  $TE_{11}$  and  $TM_{01}$  propagating modes. The correct system operation arises with the selection of the radially polarized  $TM_{01}$  mode that is ensured by means of a discontinuous phase element placed at the entrance of the system. The built polarizer has shows an operation in excellent agreement with the theoretical design. Doughnut modes are observed at polarizer output with a very high rejection of the fundamental  $TE_{11}$  mode. Provided that micromechanical machining difficulties can be overcome, the proposed design is straightforwardly scalable to much higher frequencies in the whole THz domain. In the future, this polarizer coupled to an axicon is aimed at generating very small focal spots with enhanced longitudinal electric field for THz near field imaging purposes.

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