Linear to radial polarization conversion in the THz domain using a passive system


1 Institut FEMTO-ST, Université de Franche-Comté, UMR 6174 CNRS, Département d’Optique P.M. Duffieux, 16 route de Gray, 25030 Besançon cedex, France.

2 Institut d’Électronique du Sud, Université Montpellier 2, UMR 5214 CNRS, Place E. Bataillon, 34095 Montpellier, France.

thierry.grosjean@univ-fcomte.fr

Abstract: This paper addresses a passive system capable of converting a linearly polarized THz beam into a radially polarized one. This is obtained by extending to THz frequencies and waveguides an already proven concept based on mode selection in optical fibers. The approach is validated at 0.1 THz owing to the realization of a prototype involving a circular waveguide and two tapers that exhibits a radially polarized beam at its output. By a simple homothetic size reduction, the system can be easily adapted to higher THz frequencies.

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References and links
1. Introduction

For twenty years, considerable improvements have been brought to THz systems and the field has seen an astonishing development of its experimental tools in the inspection of materials and the spectroscopy of chemical species [1] and biological samples [2]. As experienced in the optical domain, the generation and use of radially polarized beams should have a significant impact in the evolution of research in the THz domain, especially in near-field microscopy (and derived techniques) and THz plasmonics.

At optical frequencies, these highly symmetric fields have brought an important added value in high numerical aperture focusing and conventional microscopy [3-7], single molecule probing [8], near-field optical microscopy and spectroscopy [9, 10], laser cutting [11], particle trapping and accelerating [12, 13], high-power laser emission “stability” [14, 15]. All these studies take benefit from the total field symmetry provided by radial polarization. Such a property can lead, for example, to focused fields with either a strong longitudinal component [3, 4, 16] or a p-polarization state with symmetry of revolution.

So far, only a very limited number of systems allows the generation of radially polarized THz beams. Most of them are based on the excitation of the mode sustained by metallic wires whose electric field distribution is radially distributed around the wire [17-19]. The use of photoconductive antennas with radial symmetry seems to solve the problem of coupling efficiency between THz radiation and the wire mode [18]. However, the radiation efficiency of the wire mode in free space is questionable. Recently, it has been shown that optical rectification gives an alternative solution for the generation of THz radially polarized pulses [20]. However, both systems require the design of a proper active THz source.

In this paper, we propose 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 adaptable to any kind of existing THz sources. In a first section, the principle of the proposed THz radial polarizer is described. Then, the concept is validated with a first prototype.
2. Principle of the passive THz radial polarizer

2.1. From Optics to terahertz

The wide development of the terahertz techniques is partly due to the successful transposition of some optical concepts to the THz domain. For example, the extension to THz frequencies of the well-known near-field optical microscopy has opened new perspectives in the local observation of physical and biological materials with submicrometer resolution [21-27]. We suggest here that the generation of THz radially polarized beams can also get benefits from the know-how of the optics community.

The various techniques proposed for more than 15 years for generating radially polarized light can be divided into active and passive systems. Active systems are generally conventional lasers whose cavity has been modified for radiating a radially polarized mode. These modifications consist of inserting optical components such as axicons [28-30], phase-step elements [31], birefringent crystals [32,33] or diffractive elements [34,35] into the cavity in order to select the desired mode. Despite good results in terms of polarization purities and/or efficiencies, these solutions do not appear to be well-adapted to the current THz sources. Passive systems are designed for converting linearly or circularly polarized laser beams into doughnut beams that are radially polarized. They are set outside the laser cavity and do not produce by themselves THz waves. Among the passive systems developed so far, one can find Mach-Zehnder interferometers which combine the orthogonal TEM$_{01}$ and TEM$_{10}$ modes [36-38], computer generated holograms [39], liquid crystal polarization converters [40-42], spiral phase system [43] and the mode selection inside few-mode optical fibers [44-46]. All these concepts seem to be easier to extend to the THz domain as they are not limited to a specific radiation source. The challenge is here to extend to THz frequencies the components specifically developed for the optical range.

2.2. Modes sustained by circular metallic waveguides

It turns out that the optical fibers used in Refs. [44-46] can find in metallic circular waveguides a straightforward counterpart for the generation of radial polarization in the THz domain. Figure 1 displays the classification of the allowed propagating modes of a perfectly conducting metallic cylindrical waveguide with respect to its cutoff diameter.

![Fig. 1. Classification of the first modes carried by a hollow circular waveguide of perfect metal ($\lambda$ is the wavelength).](image)

Following in wavelength, scale after the linearly polarized fundamental TE$_{11}$ mode, are the radially polarized TM$_{01}$ and the hybrid polarized TE'$_{21}$ and TE''$_{21}$ modes. Figure 2 shows the intensity distribution and electric field orientation of these first modes into a 7 $\lambda$ wide circular metallic waveguide ($\lambda$ is the wavelength). The primes on the TE$_{21}$ mode indicate that one is rotated by 45° with respect to the other. The twofold degeneracy of the TE$_{21}$ mode is a consequence of cylindrical symmetry.
2.3. Coupling efficiency between the waveguide modes and an incoming Gaussian beam

The generation of radially polarized beams with metallic cylindrical waveguides requires first, the selective excitation of the TM$_{01}$ mode and second, the efficient emission of this mode in free space. Since the concept of radial polarizer has to be independent of the configurations of THz continuous-wave sources and wavelength, it is assumed in the following that the incoming beam is a linearly polarized Gaussian beam whose beam-waist $W$ is about $10 \lambda$. Such field confinements can be obviously achieved for example with parabolic mirrors. We also assume that the waveguides are made with infinitely conducting perfect metal. Perfect metal is a good approximation of the real metals of interest over the THz spectral range. For example, in the case of aluminum, Drude model leads to complex permittivity comprised between values around $-3.6210^4 + 7.3210^6i$ at $0.1$ THz and $-1.6210^4 + 5.8510^4i$ at $10$ THz. In this portion of the spectrum, the skin depth does not exceed $\lambda/1230$. Therefore, the penetration of the THz radiation into the metal is weak enough so that the transmission loss of the guided modes can be neglected over the distance of propagation of a few tens wavelengths considered here. Let us note that this approximation is also valid for other metals as iron, gold and silver which exhibit skin depths smaller than the ones of aluminum in the THz domain [47-49].

Generally, the energy transfer from the incident beam and the various waveguide modes is investigated by means of the coupling coefficients $C_m$ defined as

$$ C_m = \frac{P_m}{P_i}, $$

where $P_m$ and $P_i$ are the powers carried by the modes and the input beam, respectively. When the incoming beams and the waveguides are much larger than the wavelength, the longitudinal components of the various fields are negligible. In that case, the powers $P_m$ and $P_i$ can be seen as the Poynting vector flow through the waveguide cross section

$$ P_i = \frac{1}{2} \Re \int r \, dr \, d\theta \, (E_i \times H_i^*) \cdot e_z, $$

$$ P_m = \frac{1}{2} \Re \int r \, dr \, d\theta \, (a_m E_m \times b_m^* H_m^*) \cdot e_z. $$

Unit vector $e_z$ defines the direction of the waveguide axis. Constants $a_m$ and $b_m$ are the components of respectively the input electric and magnetic field distributions onto the $m$-mode. Their expressions are based on the overlap integrals between the incoming and the mode field.
inside the small and the large waveguides. BOR-FDTD (Body-Of-Revolution Finite Difference
This channeling efficiency is defined as the ratio between the energies carried by the TM
and centered with respect to the cylindrical waveguide. Assuming that \((\mathbf{E}_m,\mathbf{H}_m)\) can be easily calculated by adapting the
In the following, the axis of symmetry of the input Gaussian beam is supposed to be aligned
and magnetic fields, respectively.
Figure 3(a) reports the coupling between the incident linearly polarized Gaussian incoming
beam and the waveguide modes in configurations 1 and 2, respectively. In both cases,
polarized fundamental mode. Figures 3(b) and 3(c) show the coupling efficiencies between the
and centered with respect to the cylindrical waveguide. Assuming that
The expression of the field distribution \((\mathbf{E}_m,\mathbf{H}_m)\) can be easily calculated by adapting the
Our approach for selectively exciting the upper mode TM
11 as a function of the taper angle \(\theta\).
2.4. Selection of the radial mode of a cylindrical metallic waveguide
Our approach for selectively exciting the upper mode TM
radially polarized is divided in two steps. The first one, borrowed from Ref. [46], consists of inverting the polarization direction of the input beam (configuration 1) or the fundamental waveguide mode (configuration 2) over half their cross sections. Then, the two halves are in phase opposition. Note that in configuration 1, this polarization inversion is carried out before the injection of the input beam inside the waveguide, whereas in configuration 2, it is realized inside the waveguide on the linearly polarized fundamental mode. Figures 3(b) and 3(c) show the coupling efficiencies between the Gaussian beam and the waveguide modes in configurations 1 and 2, respectively. In both cases, the energy of the fundamental mode that was solely excited without field reversal as shown in Figure 3(a), is now transferred into modes TM
and TE21 (see Figs. 3(b) and 3(c)). The maximum coupling efficiency between the incident gaussian beam and the waveguide mode TM
reaches 44% in configuration 2 (at a waveguide diameter of 13 \(\lambda\)) whereas it is limited to 28% in configuration 1 (at a waveguide diameter of 10.3 \(\lambda\)). The second step of the TM
mode selection consists of filtering out the TE21 mode. This task can be fulfilled by channeling the TM
and the TE21 modes excited in configurations 1 or 2 into a smaller hollow cylinder whose diameter is comprised between the cutoff diameters of the two modes (cf Fig. 1). In that case, only TM
(with the lower cutoff diameter) is transmitted through the small waveguide, TE21 being completely reflected. This operation can be carried out by tapering the large waveguide so that its output aperture matches the entrance aperture of the small one (see inset of Fig. 4).
Figure 4 displays the channeling efficiency of mode TM
as a function of the taper angle \(\theta\). This channeling efficiency is defined as the ratio between the energies carried by the TM
mode inside the small and the large waveguides. BOR-FDTD (Body-Of-Revolution Finite Difference
Fig. 3. (a) Coupling efficiency \( C \) between a linearly polarized Gaussian beam and the various modes sustained by a cylindrical hollow waveguide of perfect metal, as a function of the waveguide diameter. (b) Configuration 1, half the incoming Gaussian beam cross-section has been phase retarded by \( \pi \) (see inset). (c) Configuration 2, half the fundamental mode cross section initially excited has been phase retarded by \( \pi \) (as shown in the inset).

Time Domain) algorithm [51, 52] with spatial uniform mesh has been used to simulate the propagation of the mode inside the tapered waveguide. The transmission has been calculated as the normalized transmitted Poynting vector flux by the incident one. The flux in each case is determined by integrating the Poynting vector over the cylinder sections. In the case reported here, the diameters of the large and the small hollow cylinders are \( 7 \lambda \) and \( 0.9 \lambda \), respectively. As shown in Fig. 1, the small circular waveguide fulfills the condition required for transmitting \( \text{TM}_{01} \) and filters out \( \text{TE}_{21} \). The transmission efficiency of the \( \text{TM}_{01} \) mode through the system keeps lower than 5% for taper angles smaller than 62 degrees but grows rapidly for larger angles and almost reaches \( \approx 90\% \) for \( \theta = 83^\circ \) which is considered as a quasi adiabatic regime of the taper.

2.5. Efficiency of the linear to radial polarization conversion

From the study detailed above, the efficiency of the linear to radial polarization conversion can be evaluated by multiplying the efficiencies calculated previously for the two steps of the \( \text{TM}_{01} \) mode selection. Figure 5 shows the total efficiency as a function of the large waveguide diameter, for a width of the small waveguide of \( 0.9 \lambda \) and a taper angle of 80°. For this angle,
Fig. 4. 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 channeling efficiency, calculated for a diameter of 7 \(\lambda\), is about 77%. This value has been kept constant for calculating the efficiency of the radial polarizer.

Fig. 5. Efficiency of the TM\(_{01}\) mode selection as a function of the diameter of the first (large) waveguide; dashed line: configuration 1; solid line: configuration 2, configurations are detailed in §2.4.

The second configuration of polarization reversal leads to a maximum efficiency of linear to radial polarization conversion larger than 34% for a large waveguide diameter of 13 \(\lambda\) whereas the maximum efficiency of the first one is limited to 22% at large waveguide diameter of 10.3 \(\lambda\). Therefore, the configuration of radial polarizer which involves a polarization reversal inside the first (large) waveguide seems to be better adapted for radially polarizing THz waves.

2.6. Far-field emission

Because the TM\(_{01}\) mode frequency is close to the cutoff inside the small waveguide, the free space radiation efficiency of the polarizing device is not maximum. This problem can be solved by placing a circular horn antenna at the end of the small waveguide for adapting the electromagnetic impedance of the output TM\(_{01}\) guided mode to vacuum.
Prototype design and fabrication

Figure 6 depicts the preliminary system aimed at validating the above presented concept of radial polarizer at a frequency of 0.1 THz. It consists of a tapered waveguide coupled to a discontinuous phase element (DPE). The latter is a dielectric plate whose output interface exhibits a step. The step height \( h = \lambda / 2(n - 1) \) induces a \( \pi \)-phase retardation for the thicker part of the plate with respect to the thinner one when a radiation goes through the system at normal incidence. When the step is orthogonal to the direction of the incident linear polarization, the DPE induces the desired phase conversion for the generation of radial polarization (Fig. 7). Such a dielectric system is widely used in optics for the generation of radially polarized beams [53, 31, 38, 46].

![Fig. 6. Schema of the first radial polarizer prototype. It is composed of a DPE and a focusing waveguide system.](image)

![Fig. 7. Effect of the DPE onto the incident free space Gaussian beam. The waveguide modes excited with and without DPE are also indicated.](image)

The DPE is fabricated by micromachining a 3.5 mm high step onto one of the two faces of a polytetrafluoroethylene (PTFE) plate whose index of refraction \( n \) is close to 1.43 at 0.1 THz. The DPE is set outside the waveguide system in order to finely center the phase step with respect to the waveguide entrance aperture thanks to a precision translation stage. As discussed in §2.4, the fine positioning of the DPE outside the waveguide system is made at the expense of some loss of efficiency.

The focusing waveguide system has been fabricated by micromachining an aluminum rod. At its heart, a 6 mm long hollow cylindrical waveguide of 2.7 mm (0.9 \( \lambda \)) diameter 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 $\approx$ 40 mm for channelling an incoming 30 mm ($10 \lambda$) wide Gaussian beam to the small waveguide. Adiabatic conversion of the free-space propagating mode is ensured by a taper angle $\theta$ higher than $80^\circ$ of resulting attenuation $\leq$ 1.1 dB as a result of calculations of Fig. 4. The output of the waveguide is also tapered but to a limited diameter of 4 mm. This circular horn antenna ensures a sufficient power density at the output aperture with an enhanced free space radiation of the system. Relatively high intensities at the system output are required for the detection of the radially polarized beam with low efficient micro-probes.

2.8. Simulation of the prototype

A preliminary numerical study of the ability of this prototype to polarize radially THz radiations is conducted by using a home-made BOR-FDTD code. This latter is based on the discretization of the Maxwell equations when they are expressed in cylindrical coordinates. By this way, the axis-symmetry of the structure is fully analytically treated to reduce the dimension of the studied problem by explicitly expressing the azimuthal dependence in Maxwell equations. This leads to consider a 2D meshing in the $(r, z)$ space instead of a 3D one for the three cylindrical coordinates $(r, z, \phi)$. Because aluminum shows very high permittivities in the THz domain [47], transmission losses inside the metallic structure are negligible and the prototype has been modelled with perfect metal for convenience.

In Fig. 8, the transmission through the waveguide system is evaluated for two incoming free space eigenmodes with (Fig. 8(a)) radial and (Fig. 8(c)) hybrid polarizations. These two modes are supposed to be coupled to the TM$_{01}$ and TE$_{21}$ modes inside the metallic structure, respectively. In both cases, the injection plane is located at 20 mm in front of the entrance facet of the device. The field distributions of the input beams in the injection plane are the ones of the TM$_{01}$ (Fig. 8(a)) and TE$_{21}$ (Fig. 8(c)) guided mode of a cylindrical waveguide at the desired frequency. These initial conditions are calculated using a N-order FDTD code [54] especially elaborated for the determination of the eigenfrequencies of an axis-symmetrical structure [55].

Figures (8(d) and (f)) show that the radially polarized incident beam (coupled to mode TM$_{01}$) is transmitted through the system (Fig. 8(d)) whereas the incoming beam with hybrid polarization (which couples to mode TE$_{21}$) is stopped at the entrance of the hollow cylinder waveguide (Fig. 8(f)). For a better view of this phenomenon, the fifth root of the electric intensities are represented in Fig. 8(d,e,f). Note that the length of the cylinder is larger than the evanescent tail of TE$_{21}$ inside the waveguide. This explains the negligible output far-field re-emission of this mode (Fig. 8(i)). The transmission of the degenerated mode that is usually produced by the DPE (Figs. 8(b,e,h)) can be simulated simply by adding the field distributions calculated in the two last cases. We see that the two lobe incident field distribution (Fig. 8(b)) is converted into a doughnut output beam that is related to the selective transmission of the TM$_{01}$ mode radially polarized through the metallic structure (Fig. 8(h)). An efficiency of 11% has been calculated for this preliminary configuration of waveguide system. Note that this value do not take into account the reflections of the input beam onto the interfaces of the DPE.

3. Experimental setup

The experimental setup of generation and characterization of the radially polarized beam is sketched in Fig. 9. A continuous-wave linearly polarized radiation is generated at 0.1 THz. The source is an electronic synthesizer followed by a sextupler from Spacek Labs Inc. Available operating bandwidth of this commercial system is 75-110 GHz with a nearly constant 0 dBm output. A WR10 horn antenna is connected to the source for improving the free space radiation efficiency. After their collection and collimation with a parabolic mirror, waves propagate under...
Fig. 8. FDTD simulation of the focusing waveguide system. The real case is simulated in the middle column whereas the right and left columns show the projection of the field distribution in a basis of eigenmodes. We see that the degenerated space mode (b) that is produced with the DPE is the result of the combination of (a) a radially polarized mode and (c) a four-spot mode with hybrid polarization. (d,e,f) show the fifth root of the electric intensities in a longitudinal cross-section of the device for the three input modes. (g,h,i) exhibit the electric intensities in a lateral plane located at 15 mm from the output side of the device.
a form close to a Gaussian beam whose waist is about 30 mm (10 λ), as shown in Fig. 10(a).

The polarization converter is placed into the THz beam so that the DPE is set close to the beam waist and the waveguide system is positioned in contact to the DPE. The waveguide is carefully centered and aligned with respect to the incoming beam propagation axis. The DPE can be translated transversally with a 1D translation stage that ensures an accurate centering of the DPE phase step with respect to the waveguide input aperture. Detection involves a Schottky diode coupled to a PTFE pyramidal probe of principle similar to the one described in Ref. [56]. The probe was built from a WR10 waveguide (inner sizes 1.27 mm × 2.54 mm) filled with a PTFE parallelepiped ended by a pyramid of 3 mm height protruding from the waveguide end. The two opposite largest facets of the tip were metal coated using Ni pulverization. The sensitive end facet area exhibits dimensions of 20 × 40 µm. The detection provided by this tip is thus specially engineered to be polarization sensitive since this collection system picks up only one transverse component of the electric field. The distance between the polarizer end facet and the probe is kept lower than 0.2 mm (λ/15) during image acquisitions by raster-scanning. The probe system is mounted onto a 2D motorized translation stage, with optimal resolution of 100 nm, for scanning the end aperture of our device.

4. Results and discussion

Figure 10 shows the properties of the field before and after its transmission by the waveguide system when the DPE is removed. Images in Fig. 10(b) reports the intensity of the field components parallel and perpendicular to the incident polarization direction as observed at the waveguide system end. Those images have been taken by two successive acquisitions, with a scan step of ≈ 200 µm and by rotating the probing device by 90° between the two scans. As a major consequence, the upper part of the Fig. 10(b) displays a bright spot whereas the lower part shows an intensity distribution which just exceeds the detection background. These images demonstrate that the output field distribution is linearly polarized along the polarization direction of the incoming beam. Such a polarization property is due to the excitation of the TE_{11} mode inside the waveguide structure.

The acquisitions realized with the DPE in front of the focusing system are reported in Fig. 11. Images obtained when the axis of the polarizing probe stage is set parallel and perpendicular to the incoming polarization direction are displayed in Figs. 11(a) and 11(b), respectively. These orientations are indicated by white arrows on each image. A numerical reconstruction of the outgoing beam from Figs. 11(a) and 11(b) is provided in Fig. 11(c) whereas cross-sections of Fig. 11(a) along the horizontal direction (solid curve), and Fig. 11(b) along the vertical direction...
Fig. 10. (a) Measured intensity before the DPE (dots) compared with a theoretical gaussian beam (solid line). (b) Images of the transmitted intensity obtained without DPE when the polarizing probe axis is parallel (upper part) and perpendicular (lower part) to the incident polarization direction. Intensities are normalized to the same maximum value for both images.

(dashed curve) are plotted in Fig. 11(d).

Two-grain structures jump out in Figs. 11(a) and 11(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 (see Fig. 11(d)) 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. 11(a) and 11(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 detection tools that we used. This is partly due to the fact that there is no direct coupling between a radially polarized beam and the fundamental mode of a rectangular waveguide. From the discussion of §2.4, it can be enhanced by inserting the DPE inside the focusing structure. This can be achieved, for example, by adapting a cylindrical waveguide to the entrance of the focusing taper. This will be made in a close future for fabricating the first THz experiments involving radial polarization.
Fig. 11. Acquisition results of the field distribution transmitted by the prototype over a scan of $7 \times 7 \text{ mm}^2$. (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). (d) Horizontal cross-section of (a) (solid curve) and vertical one of (b) (dashed curve).
5. 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. A nearly optimum design of such a passive radial polarizer has been given owing to numerical FDTD calculations of the coupling efficiency of a Gaussian propagating linearly polarized beam to the TM$_{01}$ mode of a large circular waveguide. Aperture size of this input cylindrical waveguide as well as the design of the taper that follows have been optimized. The experimental realization has been conducted at 0.1 THz. The built polarizer has shown an operation in excellent agreement with the theoretical design. Doughnut modes have been 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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