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Efficient coupling of propagating broadband terahertz radial beams to metal wires

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At present, most terahertz (THz) technologies rely on free propagation rather than waveguide transportation. These systems have limitations such as large diffraction, and bulky volume, THz waveguides provide a promising approach to overcome these hurdles. However, in THz range, efficient wave-guiding is challenging, owing to the high loss from the finite conductivity of metals or the high absorption of dielectric materials in this spectral range, and also wide band of this range (0.1-10 THz) makes it difficult to find a guiding scheme without obvious dispersion. Bare metal wires, which support a plasmonic mode, on their surfaces in THz range, are one of good candidates for THz waveguides with low loss and low dispersion [1]. Nevertheless, large mismatch between radially polarized mode in a metal wire waveguide and linearly polarized mode in a free space hampers efficient coupling. Thus, coupling efficiency reported so far is lower than 0.5% [1, 2]. Several attempts to increase the coupling efficiency of metal wire waveguides have been made by controlling the spatial mode of THz wave. Radially symmetric antennas [2], mode filters [3], plasmonic in-couplers [4, 5], or directly generating radial modes on metal wires [6] are tried to realize high coupling efficiency. Yet till now, to our knowledge, efficient coupling of broadband propagating THz wave to bare metal wires is not realized, and experimental investigations to determine coupling efficiency are not performed.

Recently, we have developed a new method to generate broadband and stable THz cylindrical vector beam [7], which is a promising candidate to realize efficient coupling to a metal wire [2]. In this study, we demonstrate efficient coupling to metal wires from propagating mode by introducing broadband THz radial beams. In our setup, a mode converter with 8-piece segmented half wave-plate is used to transfer linearly polarized laser beam to a predesigned vector mode with spatially controlled polarization state. When a three-fold rotation symmetric nonlinear crystal is excited by this mode, radially polarized THz beam is radiated (Fig.1). The image of intensity distribution taken by THz camera shows that the radial mode quality is improved in comparison with our earlier results [7]. This THz radial beam is focused by a THz lens (f = 50 mm) to an end of a copper wire with 20 cm length and 1 mm diameter, which is held by polytetrafluoroethylene (PTFE) holders. A photo-conductive antenna is placed at the other end of the copper wire for a scanning THz time-domain spectroscopy.

Scanning result at the output end of the copper wire shows the radial guided mode clearly (Fig.2). Waveforms and spectra at in-couple and output plane are shown in Fig.3. The spectrum of the guided wave is extended to as high as 2.0 THz, which is much higher than 0.5 THz in Ref. 1. A comparison between frequency dependence of input energy (scanned at in-couple plane in Fig.1) and output energy describes frequency dependence of energy coupling efficiency (Fig.4). The maximum coupling efficiency is as large as 60% at approximately 0.4 THz, while in total 29.6% of propagating THz radial mode energy is coupled to the copper wire. Numerical simulations are performed, and the results have a good correspondence with experiment data (Fig.4). Based on theoretical analysis, parameters to increase bandwidth of efficient coupling will be discussed.

This high-efficiency coupling method should be important to develop new THz manipulation technologies and THz remote sensing.

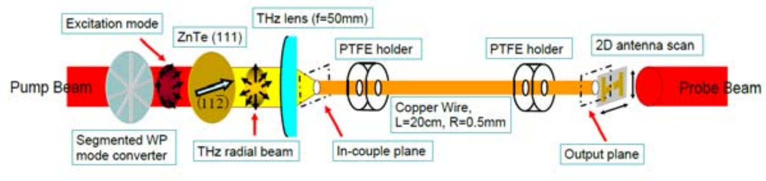

Fig.1 Setup of metal wire wave-guiding

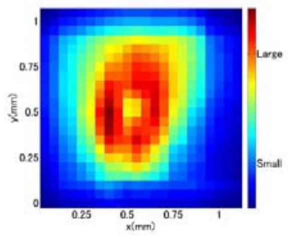

Fig.2 Intensity distribution at output plane

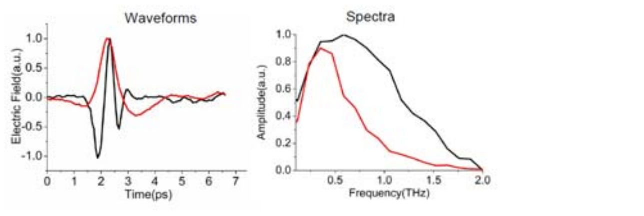

Fig.3 Waveforms and spectra (Black: In-couple plane; Red: Output plane)

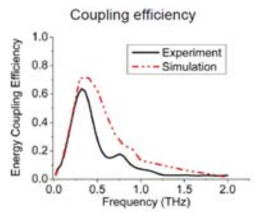

Fig.4 Frequency dependency of coupling efficiency

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