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Metamaterial hyperlenses for extreme sub-diffraction focusing of THz radiation

Juliano G. Hayashi^{1,2}, Richard Lwin¹, Alexander Argyros¹, Simon Fleming¹,
Boris T. Kuhlmei^{1,2} and Alessio Stefani^{1,3}

¹*Institute of Photonics and Optical Science (IPOS), School of Physics, University of Sydney, NSW, Australia*

²*Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, NSW, Australia*

³*DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
alessio.stefani@sydney.edu.au*

Abstract: Extreme sub-diffraction focusing of THz radiation is obtained by cascading two metamaterial wire array fiber hyperlenses. A record $1/176$ of the wavelength is achieved, allowing squeezing 8.8 mm wavelength to a 50 micron spot.

OCIS codes: (160.3918) Metamaterials; (110.6795) Terahertz imaging

1. Introduction

THz frequencies, corresponding to millimeter wavelengths (λ), are important topics in the fields of imaging and spectroscopy. However, the size of the wavelength and the consequent resolution limit causes skepticism about waves in this regime, especially concerning imaging. The scale of the wavelength results in resolution orders of magnitudes lower than visible microscopy. Attempts to overcome this limitation have exploited plasmonic waveguides [1-3] and metamaterial hyperlenses [4] to achieve sub-diffraction focusing.

The use of metamaterials, and in particular wire arrays with hyperbolic dispersion due to the strong metamaterial anisotropy, allows the propagation of high spatial frequencies, containing sub-diffraction information [5]. Hyperlenses are hyperbolic metamaterials that not only can propagate high spatial frequencies, but also transform high spatial frequencies to lower ones enabling magnification and propagation of sub-resolution details. As an optical element, the process can be reversed and the hyperlens can be employed in a focusing configuration, compressing all spatial frequencies making it possible to focus the radiation below the diffraction limit.

Sub-diffraction focusing at THz frequencies was initially demonstrated using a tapered indium wire array hyperlens embedded in a polymeric matrix (Zeonex) [4]. Focusing of $\lambda/28$ was achieved with an 8x magnification taper. Further scaling of the structure necessary to push the limit even more was limited by the fabrication. Ultimately, Plateau-Rayleigh instability sets the minimum size of wires achievable with the materials used to a few microns [6]. When fabricating smaller wires, the diameter of the wires fluctuates and the wire array structure is strongly distorted. To overcome this limit a change in materials is necessary and the use soft-glass metamaterials allows the realization of smaller and still uniform structures [7] as the rheological properties shift the instability to wire diameters of hundreds of nm. Here, we report focusing of THz radiation to $\lambda/176$ cascading the polymer hyperlens with a soft-glass one, creating a configuration with huge potential for near and far field imaging.

2. Results

The hybrid hyperlens obtained by concatenating the two different hyperlenses is shown in Fig. 1(a). The larger hyperlens consists of 473 hexagonally spaced indium wires in Zeonex, while the smaller one has 462 tin wires in a soda-lime matrix. The wire diameter (d_{wire}) through the taper reduces from 160 to 20 μm in the first hyperlens, with the separation (Λ) decreasing from 400 to 50 μm , (Fig. 1(b) and 1(c)). In the second hyperlens d_{wire} reduces from 10 to 2.5 μm , while Λ decreases from 20 to 5 μm (Fig. 1(d) and 1(e)). The total magnification of the hybrid hyperlens is calculated as the multiplication of the two separate magnification factors (8x for the polymer and 4x for the glass hyperlens), resulting in a 32x expected magnification.

A THz time-domain spectroscopy [8] experiment was performed, as represented in Fig. 1(a), to measure the transmission of the hyperlenses and determine the overall focusing capability. At the input, the THz pulse was focused using a Teflon lens (25 mm focal length) and limited in size by a 1.5 mm diameter pinhole attached to the large side of the polymer hyperlens (Fig. 1(f)). Alignment was performed to maximize the power coupled and focused by the hybrid hyperlens. The output field was measured with a near field antenna scanning a 2D area of 200 x 200 μm , with a spatial step of 5 μm . The resulting focused images are shown in Figs. 1(g-i) for frequencies of 0.034 THz (g), 0.058 THz (h), and 0.072 THz (i). The fields are elongated in the x-directions because of the diffracting ordinary waves excited by the y-polarized input. In the y-direction, instead, extraordinary waves are excited by the y-polarized signal and propagate without diffracting in the metamaterial.

To assess the extent of focusing we analyzed the FWHM of the intensity profiles presented in Figs. 1(g-i) along the y-axis. The 1.5 mm circular distribution at the input resulted in a y-direction focusing to $50 \pm 5 \mu\text{m}$ (at

0.034 THz, $\lambda \sim 8.8$ mm), 60 ± 5 μm (at 0.058 THz, $\lambda \sim 5.2$ mm) and 70 ± 5 μm (at 0.072 THz, $\lambda \sim 4.2$ mm), corresponding to approximately $\lambda/176$, $\lambda/87$, and $\lambda/60$, respectively.

Fig. 1. (a) Scheme of our combined polymer and glass metamaterial hyperlenses used in the focusing experiment. Pictures of the fibres on every interface. (b) Region 1, $d_{\text{wire}} \sim 160 \mu\text{m}$ and $\Lambda \sim 400 \mu\text{m}$. (c) Region 2, $d_{\text{wire}} \sim 20 \mu\text{m}$ and $\Lambda \sim 50 \mu\text{m}$. (d) Region 2, $d_{\text{wire}} \sim 10 \mu\text{m}$ and $\Lambda \sim 20 \mu\text{m}$. (e) Region 3, $d_{\text{wire}} \sim 2.5 \mu\text{m}$ and $\Lambda \sim 5 \mu\text{m}$. (1(b) and 1(c) from ref. [4]). (f) Image of the large side of the polymer hyperlens covered with a 1.5 mm pinhole. Focused image of the pinhole after the hybrid hyperlens, probed with a near field antenna, for different frequencies: (g) 0.034 THz ($\lambda \sim 8.8$ mm), (h) 0.058 THz ($\lambda \sim 5.2$ mm), and (i) 0.072 THz ($\lambda \sim 4.2$ mm).

Assuming perfect focusing and a 32x scaling factor, the focused image of the 1.5 mm pinhole is expected to be ~ 47 μm in the y-direction. A good agreement to this value is found with the 50 μm size measured at 0.034 THz. A small difference is found at the other two frequencies shown in Figs. 1(h,i), which is close to the experimental error. Moreover, non-achromatic coupling and diffraction in the gap between the hyperlens and the finite resolution of the near field antenna (~ 20 μm) could explain such discrepancy.

Concerns might arise due to the high optical loss of glass at THz frequencies. However, given the short length of the tin/soda-lime hyperlens (3 mm), the loss due to the material absorption of the glass is limited and a considerable amount of power was measured after the hybrid hyperlens. Further reduction of the structure on the small side, leading to larger magnification and tighter focusing is still possible: we have been able to achieve structures 10x smaller compared to the one used in the measurements, while analysis of our system indicates that we could push it even further reaching a magnification factor of 100x in the solely glass hyperlens. If combined with the polymer hyperlens, this improved hybrid hyperlens could achieve focusing of $\lambda/1600$. In this regime the optical loss due to both the glass absorption and the metal loss need to be reconsidered. We have performed finite element simulations (COMSOL) of an indefinite wire array medium and considered the effect of reducing the wires diameter. As expected, the loss increases rapidly for small wire sizes. For the smallest structure reported in the experiment, the loss is 7.5 dB/mm at 100 GHz, but only a very short section of the taper experiences such loss. This number increases to 70 dB/mm for 0.5 μm diameter wires. Considering a maximum acceptable 30 dB loss for the hybrid hyperlens, the modeling indicates that we could have a magnification factor as high 160x, which would improve our actual result to $\lambda/938$.

3. Conclusion

We have experimentally demonstrated extreme sub-diffraction focusing of THz radiation up to $\lambda/176$ by combining two metamaterial hyperlenses. The demonstration here reported shows great potential to beat the best focusing of THz radiation achieved so far with plasmonic waveguide ($\lambda/260$) [1]. Furthermore, our hybrid hyperlens is compact and has the potential to perform super-resolution imaging in the near and far field.

4. References

- [1] Zhan et al., "Superfocusing THz waves below $\lambda/250$ using plasmonic parallel-plate waveguides," *Opt. Express* 18(9), 9643-9650, 2010.
- [2] M. Awad et al., "Tapered Sommerfeld wire terahertz near-field imaging," *Applied Physics Letters*, v. 94, n. 5, p. 051107, 2009.
- [3] V. Astley et al., "Characterization of terahertz field confinement at the end of a tapered metal wire waveguide," *Appl. Phys. Lett.* 95(3), p. 031104, 2009.
- [4] A. Tuniz et al., "Metamaterial fibres for subdiffraction imaging and focusing at terahertz frequencies over optically long distances", *Nat. Commun.* 4, 2706, 2013.
- [5] P.A. Belov et al., "Experimental demonstration of multiwire endoscopes capable of manipulating near-fields with subwavelength resolution," *Appl. Phys. Lett.* 97(19), 191905, 2010.
- [6] O. T. Naman et al., "Indefinite media based on wire array metamaterials for THz and Mid-IR," *Adv. Opt. Mater.* 1(12), 971977, 2013.
- [7] J.G. Hayashi, *Wire Array Infrared Metamaterial Fibres: Fabrication and Applications*, PhD, University of Sydney (2017).
- [8] D. Grischkowsky et al., "Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors," *Journal of the Optical Society of America B*, 7(10):2006–2015, 1990.