Design and Performance of Plasmonic Lenses Optimized for 325 GHz

David A. Naylor[1], Tanner J. Heggie[1], Brad G. Gom[1], Grace Trimboli[1] and Evgueni V. Bordatchev[2]
[1]University of Lethbridge, Lethbridge, AB, T1K 3M4 Canada
[2]National Research Council of Canada, London, ON, N6G 4X8 Canada

***Abstract*— Imaging applications at terahertz (THz) frequencies are limited to relatively low spatial resolution due to the effects of diffraction. A subwavelength aperture can be used to improve the resolution at the cost of low transmission. Plasmonic lenses in the form of bullseye structures, consisting of a single subwavelength circular aperture surrounded by concentric periodic corrugations, have shown enhanced transmission and beam confinement. In this paper, we discuss the design and performance of plasmonic lenses optimized for transmission at 325 GHz.**

I. INTRODUCTION

THE discovery of extraordinary transmission (EOT) of light through subwavelength hole arrays by Ebbesen[1] led to rapid growth in the field of plasmonics. The focus of much of this research occurred at visible wavelengths to enhance transmission through subwavelength metallic hole arrays, slits, and bullseye (BE) lenses[2]. BE lens designs typically have surface structures that can be viewed as either grooves or ridges along the input and/or output faces of the lens surrounding a circular aperture. Surface plasmon polaritons (SPPs) resonantly excited by the periodic corrugations on the input side of the lens lead to enhanced transmission, while corrugations on the output side of the lens serve to couple SPPs back to the radiation field. Phase delays induced by the geometrical structure lead to interference effects that can be used to control the propagation direction of the output beam.

Two factors simplify the design and fabrication of BE lenses operating at THz frequencies: firstly, metals behave as perfect electrical conductors; secondly, the dimensions of the geometric structure of the lens are such that micro- rather than nano-fabrication techniques can be employed.

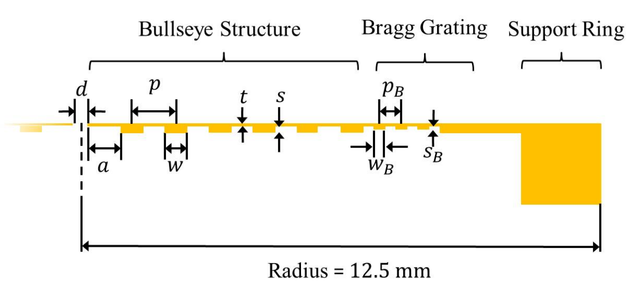

Fig. 1. The design parameters for a single-sided bullseye lens.

II. THEORETICAL

A numerical Maxwell equation solver[3] has been used to optimize the THz transmission through BE lenses having a range of surface structures summarized in Fig. 1. The optimum design parameters of our THz BE lens are shown in the first row in Table 1. The as-built parameters of a single-sided (SS) and double-sided (DS) BE lens are also presented.

Table 1. Design and as-built parameters for a bullseye lens optimized for THz frequencies (Fig. 1).

	d	t	a	p	w	s	p_B	w_B	s_B
Design	300.0	50.0	1110.0	890.0	444.0	130.0	444.0	222.0	65.0
SS	299.8	48.6	1119.6	890.4	445.2	129.0	448.8	224.4	66.6
DS	298.8	37.4	1110.9	891.8	445.9	130.2	447.0	223.5	66.1

In addition to determining the enhanced transmission, the modeling software has been used to develop a phenomenological phase modulation model, which describes the relative phase difference, $\varphi_{i,0}$, between light travelling through the central aperture, φ_0, and that scattered from the surface corrugations, φ_i[4]:

$$[(f^2+(ir_i)^2)^{1/2} - f]k + \varphi_{i,0} = 2\pi m,\ m = 0, \pm 1, \pm 2, \ldots \quad (1)$$

This equation can be solved for the i^{th} ring, at a radial distance r_i, wavenumber k, and phase $\varphi_{i,0}$, to determine the effective focal length, f, of the plasmonic lens. To illustrate the application of the phase modulation model, Fig. 2 shows the cross section of the beam profile of a BE lens designed to have a focus at 3 mm. The location of the focus derived from the model occurs at 3.23 ± 0.06 mm.

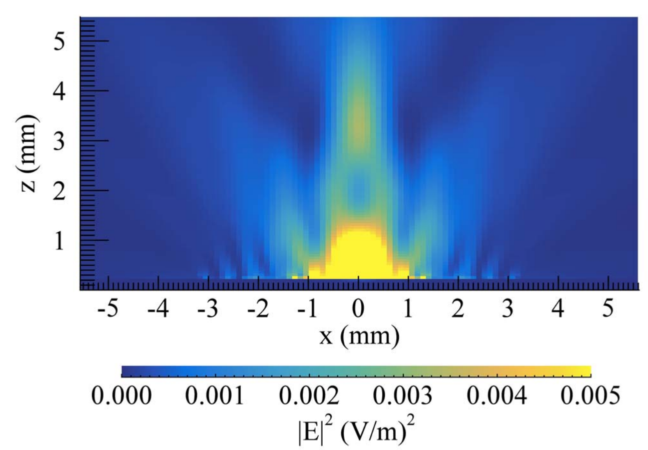

Fig. 2. Cross-section of simulated beam profile produced by a BE lens consisting of 6 output rings. The lens was illuminated by a 325 GHz plane wave. The simulated focus was found to occur at 3.23 mm, in close agreement with the design.

III. EXPERIMENTAL

The technique summarized above was used to optimize the design of several SS and DS BE plasmonic lenses and will be described in detail elsewhere[5]. In order to test the performance of the fabricated plasmonic lenses, a THz test bed was constructed, shown in Figure 3.

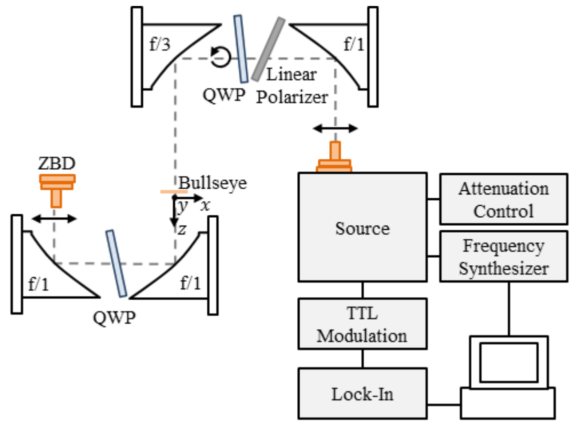

Fig.3. Schematic of the THz testbed used for transmission measurements. A predominately Gaussian, horizontally polarized, THz beam is produced by a VDI line source and is optically isolated using a quarter wave plate (QWP). Input optics, f/1 and f/3 90° off-axis parabolic mirrors (OAPs), produce an intermediate image plane having a waist radius w_0 = 5.1 mm at the location of the BE lens. The output optics (f/1 and f/1 90° OAPs) direct the beam through a second QWP to a zero-biased diode (ZBD) detector.

IV. Results

The THz test bed has been used to measure the profile of the beam by displacing a knife-edge at the location of the plasmonic lens. Fig. 5 shows that the beam is well described by a Gaussian profile.

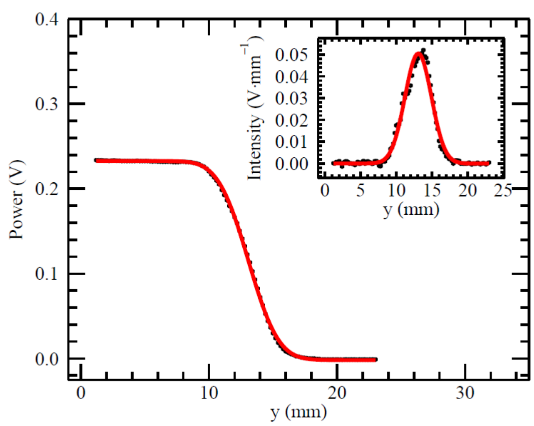

Fig. 4. Measured (black) S-curve with an error function fit (red) at the focus of the Gaussian beam. Inset: the corresponding Gaussian beam profile overlaid with the derivative of the error function fit.

The enhanced transmission, *G*, for the SS and DS lenses (Table 1) has been measured with the THz test bed shown in Fig. 3. The measured values of the enhancement are shown in Table 2 and are in excellent agreement with the enhancement determined from FDTD modelling of $G = 38 \pm 3$ at ~330 GHz.

V. Application

The SS plasmonic lens, described in Table 1, has been integrated into a THz imaging microscope, whose configuration is similar to that of the THz test bed, to obtain images

Table. 2. Measured transmission enhancement for the SS and DS BE lens. The reference taken as the SS lens illuminated on the planar surface.

Design	Illuminated Face	*f* (GHz)	Signal	Gain
Single Sided	Planar	329.500	51.9 ± 0.1	--
Single Sided	Input Rings	328.030	1997 ± 3	38.5 ± 0.1
Double Sided	Input Rings	329.875	1981 ± 3	38.2 ± 0.1

of paraffin embedded rat brain. Fig. 5a shows the image of a rat brain sample taken with the THz imaging system, which can be compared directly with the optical image shown in Fig.5c. In many studies of tissue samples, boundary determination is important. Fig. 5b shows the boundary of the THz image as determined by application of a Sobel filter[6]. The spatial resolution of the Thz microscope has been independently verified by measurements of a calibration target. The measured resolution of 338 μm is in good agreement with the 300 μm aperture of the plasmonic lens, confirming subwavelength imaging.

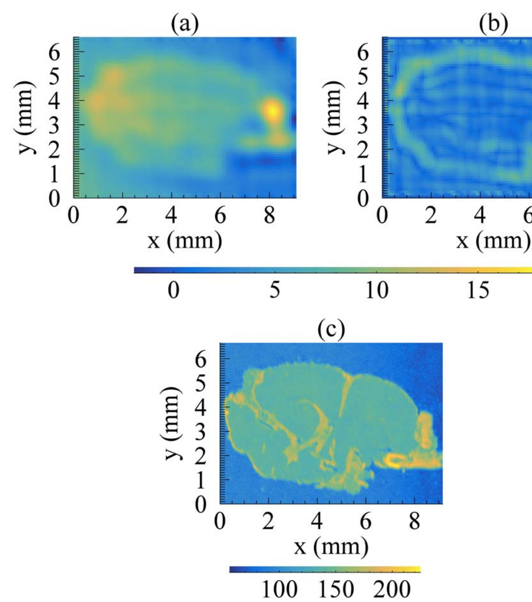

Fig. 5. Images of parrafin rat brain. (a) THz image, (b) edge detection of the THz image with an applied Sobel filter, and (c) optical image. Several features can be identified in both the THz and optical image.

References

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