Subwavelength focusing in the infrared range using a planar metallic lens of binary slits with refractive index modulation

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ABSTRACT

In this paper, we demonstrate a plasmonic planar lens structure that can achieve subwavelength focusing of the infrared electromagnetic radiation. The lens is composed of metallic binary slits with different dielectric fillings. The index modulation approach of the filling materials is used to achieve phase modulation of the wavefront of the incident wave. Using this approach, we could achieve a phase range of 0.43π. The structure can focus the incident infrared wave in the subwavelength scale. The focal length attained is 44.69 µm and the achieved Full width at half maximum (FWHM) is 4.28 um for an incident infrared wave of wavelength 8 um. The transmission through the structure is 25.64 % at the design wavelength. The used metal is copper and the dielectric filling materials are silicon and air. Copper has lower losses in the infrared range than the traditional metals used in visible Plasmonics. Silicon has a higher melting point than the common dielectric materials used in refractive index modulation of the visible Plasmonic lenses. This temperature stability is a very important feature when working in the infrared domain. Besides being specifically suitable for the infrared range, copper and silicon are also CMOS compatible. Therefore, the proposed structure is suitable for integration in many potential infrared applications such as thermal imaging, medical diagnosis, thermal photovoltaic cells and heat harvesting. In addition, the fact that many molecules have unique absorption spectra or signature in the infrared range would facilitate the analysis and study of many materials and biological molecules using infrared miniaturized spectrometers.

Keywords: Infrared focusing, planar lens, subwavelength focusing, plasmonics, binary slits, phase modulation.

1. INTRODUCTION

In 1998, a strange phenomenon was observed where a screen of subwavelength holes transmitted more light than was expected from the total area of the holes. This phenomenon was known as extraordinary optical transmission (EOT) [1]. Subsequent studies showed that the phenomenon could be due to the excitation of surface plasmon polaritons (SPPs) [2, 3]. A theoretical analysis of plasmonic effects in silicon-filled metallic nanoholes is given in [4].

The EOT has opened the way to many subwavelength structures and devices such as the plasmonic lens which received great attention in the past few years that followed the discovery of the EOT phenomenon [5-20].

Different phase modulation techniques were employed to make subwavelength plasmonic lenses in the visible range. Those approaches include depth modulation [6], width modulation [8], refractive index modulation of the filling material [11], both width and refractive index modulation [9] and finally initial phase modulation [12].

Focusing in the infrared range was reported using diffraction gratings with slight resolution and transmission [21]. Hyperbolic metamaterials were also used to achieve focusing in the mid IR range using InAs based semiconductor which is relatively expensive [22, 23] but still highly suitable for applications that might require high resolution.

Generally most of the research efforts have been concentrated on plasmonics in the visible range including the attempts to achieve subwavelength focusing of the visible radiation. However, the knowledge we got in the visible domain throughout the past decades can be transferred to the infrared domain if we used the suitable materials that could function properly in the infrared range. This is an issue because the response of the materials differs between the two domains [24].

The infrared range has distinct characteristics that enables it to be useful for different physical, chemical and biological applications [25, 26]. It can be employed in health checks. In addition, most molecules have distinct absorption spectra or signature in the infrared range. That's why it would be important to build structures or devices that can manipulate the infrared radiation in the subwavelength scale making them easier to integrate in future applications.

In this paper, we present a planar lens structure of binary slits that can focus the infrared radiation into a spot smaller than the wavelength of the incident wave. We use copper and silicon as design materials which are CMOS compatible and thermally stable in the infrared range.

The paper is organized as follows: The structure and its theoretical principle are given in section 2, simulation results are shown in section 3 and finally the paper is concluded in section 4.

2. THEORY AND STRUCTURE

In our infrared structure, we adopted the technique of refractive index modulation of the filling materials in uniform binary slits [11].

For a subwavelength metallic slit of width w and depth d, the plasmonic mode propagating in the slit would have a propagation constant β given by the relation [27]

$$\tanh\left(\sqrt{\beta^2 - k_0^{\,2}\varepsilon_d}\ \frac{w}{2}\right) = \frac{-\varepsilon_d\sqrt{\beta^2 - k_o^{\,2}\varepsilon_m}}{\varepsilon_m\sqrt{\beta^2 - k_o^{\,2}\varepsilon_d}} \qquad (1)$$

where ε_m and ε_d are the relative dielectric constants of the metal and the dielectric material filling the slit respectively, k_0 is the wave vector of the incident infrared wave in free space and w is the slit width.

To get a focusing effect, we modulate the phase of the output wave by modulating the refractive index of the filling materials in the slits. The index modulation approach was found to give a larger phase delay tuning range up to π which achieves better focusing results in comparison to the width modulation approach which shows a limited tuning range [11]. In addition, the binary slit structure is easier to fabricate compared to structures using depth or width modulation techniques [11, 12]. That's why in our work we chose the approach of refractive index modulation of the filling materials in uniform binary slits. Then with the selection of the suitable materials and design parameters, we could attain subwavelength focusing in the infrared range.

Our proposed lens is made of a copper film of depth d=2 μm. The diameter of the lens aperture is D=110 μm. The wavelength of the plane wave incident from the left side of the lens is λ =8 μm which is in the mid infrared range. The dielectric constant of copper is ε_m = -2200 + i728 at the specified wavelength [28]. There are 33 uniform slits (16 slits on each side of the central slit). Each slit has a width w=1 μm and the slits are spaced 3 μm apart from each other. The filling materials are silicon and air where the refractive index of silicon is 3.42 at the wavelength of 8 μm. A summary of the design parameters is given in table 1. A schematic of the structure is shown in figure 1.

Table 1. Design parameters of the binary slit lens with refractive index modulation.

Parameter	Value
working wavelength (λ)	8 μm
Slit depth (d)	2 μm
Diameter of the lens aperture (D)	110 μm
Width of each slit (w)	1 μm
Total Number of slits (N)	33

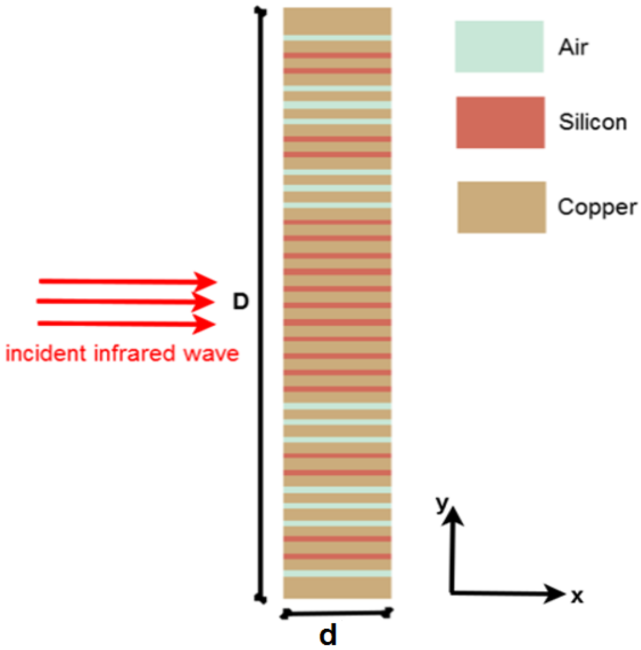

Figure 1. Design schematic of the binary slit lens showing the sequence of the filling materials.

Figure 2 shows the phase versus the slit width once at ε_d =1 (air filling) and then at ε_d = 3.42 (silicon filling). We can see that there is a phase difference of 0.43π between the silicon and the air filled slits at any slit width. Therefore, it's evident that using silicon and air as filling materials allows for a high phase tuning range. Silicon also has the advantage of being CMOS compatible and it is thermally stable at high temperatures [29] compared to the dielectric filling materials used in the visible range such as PMMA. It's critical for the lens materials to be thermally stable in order to operate appropriately in the infrared range. The choice of copper is also suitable since it has lower absorption losses in the infrared range compared to the traditional metals used in visible plasmonic lenses like gold or silver. Table 2 gives the extinction coefficient k of copper, silver and gold at the design wavelength of 8 μm [28]. We notice that copper has the least extinction coefficient which is responsible for the absorption losses in the metal. Copper is also cheaper compared to gold or silver.

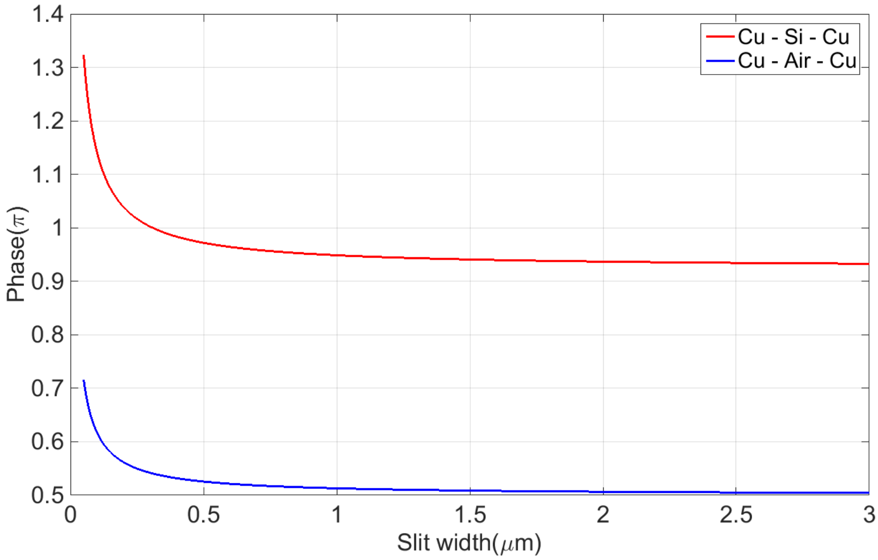

Figure 2. The variation of the phase delay with the slit width and the refractive index of the filling material (silicon and air in this case).

Table 2. The permittivity of copper, silver and gold at the wavelength of 8 μm.

Metal	Extinction Coefficient
Copper (Cu)	47.5
Gold (Au)	57.6
Silver (Ag)	57.7

3. FDTD SIMULATION RESULTS

A commercial-grade simulator based on the finite-difference time-domain method was used to perform the calculations [30]. Figure 3 shows the magnetic field intensity profile. The focal length was found to be 44.69 μm and the FWHM is 4.28 μm which is less than the wavelength of the incident infrared wave and thus we have subwavelength focusing. It's also worth mentioning that the transmission attained is 25.64 % at the design wavelength.

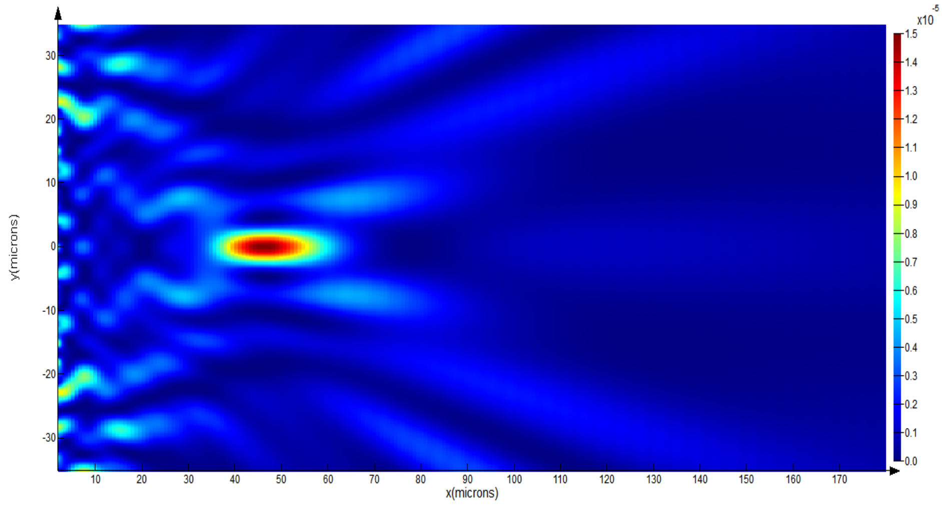

Figure 3. The magnetic field intensity distribution $|H|^2$ of the focused radiation in case of using the binary slit structure. The field intensity is measured in arbitrary units.

4. CONCLUSION

Most of the previous literature has been concentrating on visible plasmonics and its applications that include focusing the visible radiation using planar lens structures. Transferring the knowledge we possess in the visible domain to the infrared domain could open the door for many potential infrared applications. Therefore, in this paper we demonstrated a planar structure of a binary slit lens that focuses the infrared radiation in the subwavelength scale.

The structure is made of copper and it consists of uniform binary slits. The refractive index of the materials filling the slits is varied such that we obtain a phase modulated output wavefront. This phase modulation is necessary for achieving the focusing effect. Silicon and air were used as filling materials to give a phase range of 0.43π. The lens can focus the incident infrared wave into a hot spot having a FWHM of 0.53λ and focal length of 44.69 µm.

Copper was suitable for the infrared range because as a metal, it's cheaper and has lower absorption losses in this range compared to other noble metals traditionally used in visible plasmonics. Silicon was also a perfect choice because when it is used with air as filling materials, we get a phase range of 0.43π. In addition, silicon is thermally stable in the infrared range. The lens could be integrated in future applications because both copper and silicon are CMOS compatible.

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