Optics Communications 291 (2013) 390–394

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Control the dispersive properties of compound plasmonic lenses

Weiwei Wan [a,b], Changbao Ma [b], Zhaowei Liu [b,c,*]

[a] National Laboratory of Solid State Microstructures and Department of Materials Science and Engineering, Nanjing University, Nanjing 210093, People's Republic of China
[b] Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
[c] Materials Science and Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA

ARTICLE INFO

Article history:
Received 20 August 2012
Received in revised form
5 October 2012
Accepted 10 November 2012
Available online 5 December 2012

Keywords:
Compound lens
Plasmonic lens
Controllable dispersive properties
Plasmonic waveguide

ABSTRACT

We propose novel compound plasmonic lenses, which consist of metal–insulator–metal waveguides (MIMWGs) and phase zone plates (PZPs), with controllable dispersive properties. Numerical simulation results show that this new type of compound plasmonic lens is capable of not only minimizing the chromatic aberration but also rearranging the order of focal positions for incident light at visible frequencies. One chosen wavelength can be designed to have the shortest or the longest focal length. This controllable dispersive light-focusing behavior opens up new applications in the fields of hyper spectral imaging, binary optics and holographic devices.

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1. Introduction

Lenses and zone plates (ZPs) are the most fundamental optical elements that have been widely used to control light collimating, focusing and imaging. The intrinsic chromatic dispersive properties of these conventional lenses have been well studied [1]. For a ZP which focuses light by diffraction and interference, the shorter wavelength of light leads to longer focal length, as indicated by the oblique blue curve in Fig. 1. The strong chromatic dispersion of a ZP can be therefore utilized to filter out unwanted wavelengths while focusing the light of interest, as well as to obtain soft-focus image in photography [2]. On the other hand, the chromatic dispersion of a refractive glass lens is moderate as shown by the nearly flat red curve in Fig. 1, with a slope opposite to that of a ZP. This dispersion originates from a slight decrease in the refractive index of glass with increasing wavelengths [3], which may cause undesired chromatic aberration with degraded image quality in optical microscopy. A common goal of optical dispersion engineering is either to completely compensate the dispersion over a band of frequencies for multi-color imaging applications or to achieve extreme dispersions with arbitrarily designable wavelength dependence for spectroscopy applications.

Compound lenses are important elements for dispersion engineering due to their diverse properties. The focal length of a compound lens is determined by the focal length of each individual component, described by the following equation:[1].

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \tag{1}$$

Since the dispersive strength of a ZP is typically much stronger than that of a glass lens, the focal length of a glass/ZP compound lens is predominantly determined by the ZP. The limited dispersion in conventional glass lenses stems from the dispersive refractive index profiles associated with a set of existing materials, which hinders the possibilities for arbitrary dispersion engineering in compound lenses.

To overcome the afore mentioned limitations in conventional lenses, the metal–insulator–metal waveguides (MIMWGs) based plasmonic lenses become an unparalleled candidate for their strong dispersion [4–17]. The sensing [4], collimating [5], focusing [6–15] and imaging [16] of such plasmonic lenses have already been theoretically or experimentally demonstrated. However, none of the previous work emphasized on the dispersive properties of such optical devices. In this paper, we explore the dispersive properties of the MIMWG-based plasmonic lens as well as its combination with a phase zone plate (PZP), i.e. the combination of two optical elements with similar dispersive strength but opposite characteristics. The thicknesses of the MIMWGs are optimized to the minimum so that the compound plasmonic kinoform lens can function with the smallest possible loss. The focal properties of this novel compact compound plasmonic lens exhibit extraordinary wavelength dependence, which is extremely difficult to realize in conventional compound lenses with similar sizes.

* Corresponding author at: Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA.
E-mail address: zhaowei@ece.ucsd.edu (Z. Liu).

0030-4018/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.optcom.2012.11.052

2. MIMWGs based plasmonic lenses and compound plasmonic lenses

It is well known that, the dispersion relation of surface plasmon polaritons (SPPs) changes rapidly near the resonance frequency [17]. Therefore, the SPP waveguide modes, excited by transverse-magnetic (TM) polarized plane wave illumination, are also highly dispersive around the resonance frequency. We used the finite element method to calculate the complex effective mode index (n_{eff}) of a one-dimensional (1D) Ag–air–Ag [18] waveguides with different widths in the visible spectrum. As indicated in Fig. 2(a) and (b), both real ($Re(n_{eff})$) and imaginary ($Im(n_{eff})$) parts of the effective mode index increase with the decreasing width of the insulator layer. For a narrower MIMWG, more light undergoes the metallic region, resulting in a lower phase velocity and more loss. We choose a MIMWG with a width of 20 nm for the plasmonic lens design, given its large mode index change (from 1.86 to 3.37) in the visible spectrum and reasonably low loss (see Fig. 2(c)). The strong dispersion of MIMWGs allows us to modulate the phase retardation in a large wavelength range with moderate loss, which can be used to construct a highly dispersive plasmonic lens.

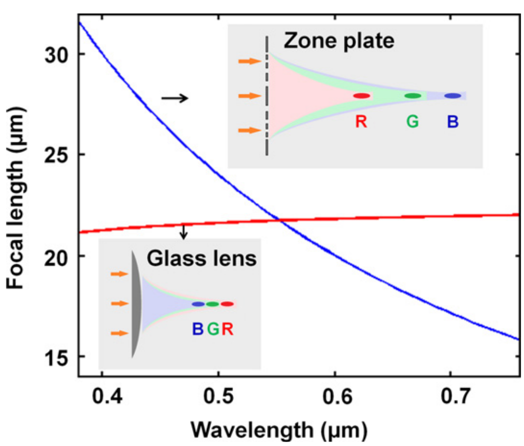

Fig. 1. Chromatic dispersive characteristics of a plano-convex lens (the flat red curve) and a zone plate (the oblique blue curve). The plano-convex lens is made of glass and the radius of its convex surface is 10 μm. The zone plate consists of alternative opaque and transparent zones. The primary focal length of the zone plate is determined by $f=k/\lambda$, where λ is the wavelength of the light and the coefficient k is set to 12 for this theoretical calculation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The MIMWG-based lens can be modeled by an effective index lens with the same shape. The effective index should be equal to the mode index of an individual MIMWG at a given wavelength. The focal positions of the effective refractive index lens are determined by the lensmaker's equation [1],

$$\frac{1}{f}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)d}{nR_1R_2}\right) \quad (2)$$

where n is the effective mode index of a MIMWG, R_1 and R_2 are the radii of each lens surface, d is the thickness of the lens. For a plano-convex lens with an infinite R_2, $1/f=(n-1)/R_1$. We want to emphasize that a MIMWG-based lens has a normal dispersion, but with the strength comparable to that of a ZP, as shown in the top panel in Fig. 3(a). Compound lenses consisting of a MIMWG-based lens and a ZP are expected to exhibit interesting dispersive properties. The focal position of such a compound lens can be derived by combining Eqs. (1) and (2), given by

$$f=\frac{R_1k}{k(n(\lambda)-1)+R_1\lambda} \quad (3)$$

where the focal length of a ZP is defined in the caption of Fig. 1. In the short wavelengths band which is near the resonance frequency, the effective mode index $n(\lambda)$ decreases rapidly, thus f increases with increasing wavelengths. Whilst for the longer wavelengths, $n(\lambda)$ changes slowly and f decreases when wavelengths increase.

3. Chromatic aberration minimization and focus order rearranging

This compound lens comprising two opposite elements with opposite dispersion leads to a unique dispersion as shown by the black solid curve in the bottom panel of Fig. 3(a). It is easy to find two wavelengths of the light having the same focal length. Therefore, a PZP can be used to compensate the chromatic dispersion of the plasmonic lenses, as shown in the inset of the

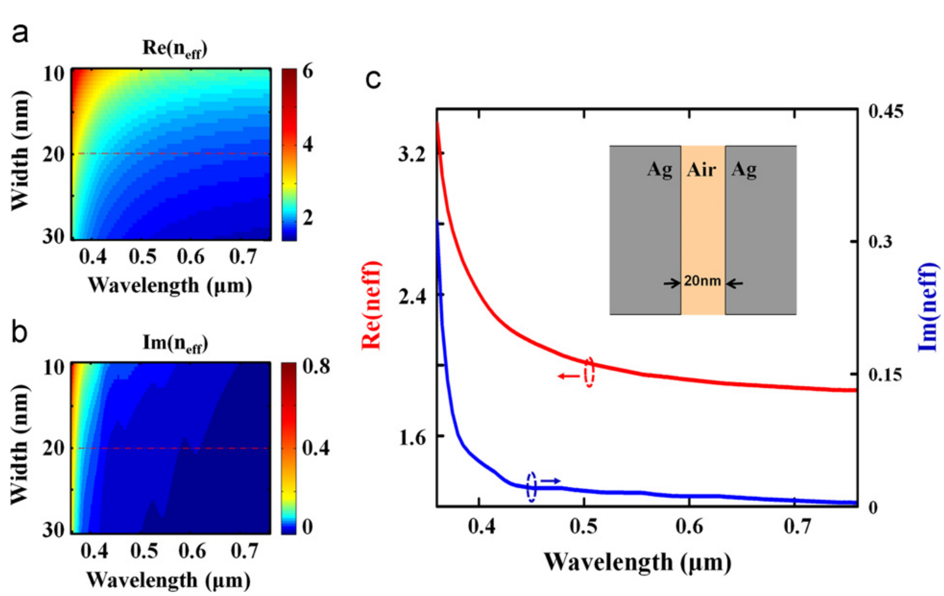

Fig. 2. (a) and (b) The real and imaginary parts of the effective mode index for a 1D Ag–air–Ag waveguide with respect to widths and wavelengths. (c) The complex effective refractive index of an Ag–air–Ag waveguide with a width of 20 nm, i.e., the dashed lines in (a) and (b).

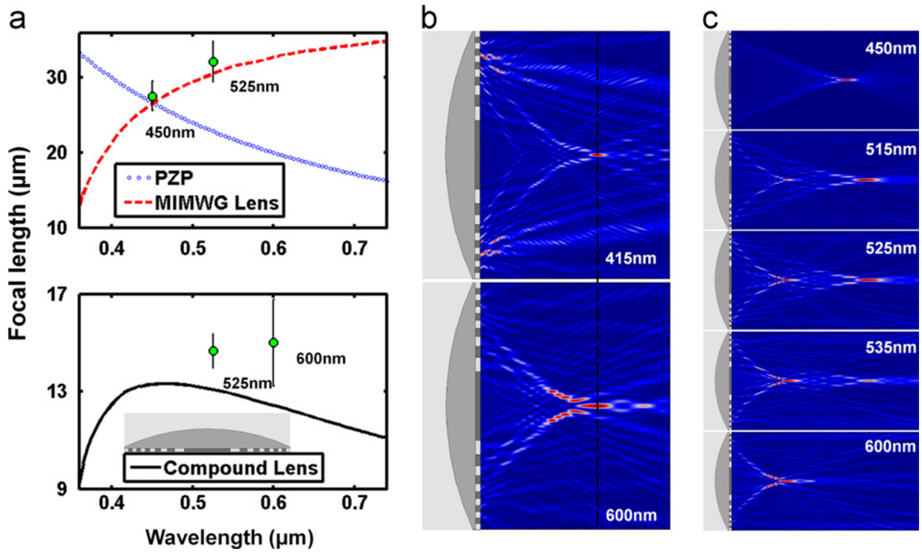

Fig. 3. (a) The focal length of a MIMWG-based lens (red dashed curve), a PZP (blue dotted curve), and a MIMWG/PZP compound lens (black) determined by Eq. (1). The PZP consists of alternative transparent and phase-shifting zones, whose indices are set to 1 and 3, respectively. The radius of the mth zone R_m is given by $\sqrt{mf\lambda+m^2\lambda^2/4}$, where m is a positive integer ($m=1, 2,\ldots$), and $f=21.43$ μm is the designed focal length at 560 nm. The outmost radius is 12.5 μm. The green circles represent the simulated positions and error bars represent the FWHM (full width at half maximum) of the foci along propagation direction. (b) Dispersion compensation for the wavelength of 415 nm and 600 nm. The thickness of the PZP is 750 nm. (c) Light focusing properties of a MIMWG/PZP compound lens at various wavelengths (450 nm, 515 nm, 525 nm, 535 nm, 600 nm). The thickness of the PZP is 450 nm. The light intensity in each of figures is normalized to itself. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bottom panel in Fig. 3(a). The MIMWG-based plasmonic lens is modeled by an effective mode index lens. The thickness of the PZP is 750 nm. The refractive indices of open zones and phase-shifting zones are set to 1 and 3, respectively. The radius of the mth zone R_m is given by $\sqrt{mf\lambda+m^2\lambda^2/4}$, where m is a positive integer. As indicated by Fig. 3(b), light with the wavelength of 415 nm and 600 nm has the same focal length. Furthermore, the chromatic dispersion over the band of visible frequencies is also significantly reduced. For the MIMWG-based plasmonic lens, the biggest difference of these focal lengths between 400 nm and 700 nm is about 13 μm. While for the compound plasmonic lens, the difference is within 2 μm. Because a PZP with fixed structures is only optimized at one designed wavelength, its wavelength dependent diffraction efficiency also plays an important role in the overall dispersive performance of this compound lens.

In the following, the same PZP but with thickness changed to 450 nm, was used to study the dispersive properties of a compound plasmonic lens. Phase shift of the light can be defined as the difference of the phase retardation between the open zones and the phase-shifting ones. At 450 nm, the phase shift is zero. The lens effect of the PZP is completely vanished so that the light is only focused by the effective refractive index lens, resulting in the focal position (the green cycle) staying on the red dashed curve in Fig. 3(a). In contrast, at 600 nm, the phase shift becomes π while the PZP reaches its maximum diffraction efficiency, making the focal position sit on the black solid curve that is determined by both lenses. The slight deviation of the simulated focal position from the theoretical estimation may originate from the neglected thickness of lenses in Eq. (1). At the wavelengths between 450 nm and 600 nm, the diffraction efficiency of the PZP spans from minimum to maximum, leading to two co-existing foci following Eqs. (2) or (3), as shown in Fig. 3(c). Moreover, the energy gradually transfers from the right focal spot to the left one when the wavelengths increase from 450 nm to 600 nm.

The wavelength dependent properties of the PZP could also be utilized to rearrange the focal orders of the visible light. As shown in Fig. 4(a), by modulating a π phase shift for green light and a zero phase shift for blue and red light, the wavefront of green light could be bent to convergence waves, while the wavefront of blue and red light remains unchanged as plane waves. Thus green light would have the nearest focus if these tailored light rays undergo a convex lens close to the PZP. Similarly, green light can be designed to have the longest focal length as shown in Fig. 4(b). The compound lens constructed by physically putting a MIMWG-based lens together with a PZP, may bring in complex fabrication processes in case of different materials in MIMWGs and PZPs. It may solve the problem by integrating a PZP into a MIMWG-based lens to form a compound plasmonic kinoform lens. First, we set a plano-convex shaped MIMWG-based lenses with the maximum thickness $h(x=0)=h_0$, and the radius of the convex curve to be r. The original thickness of each waveguide can be determined by $h(x)=h_0-(r-(\sqrt{r^2-x^2})$. Then the thickness is reduced according to the same principles for Fresnel lenses. A MIMWG-based PZP, which functions as a "switch" to modulate the phase shift of light with different colors, was finally inscribed into this thin plasmonic lens.

This kind of compound plasmonic lens consists of a series of exact 20 nm Ag–air–Ag waveguides with 200 nm spacing and various optimally reduced thicknesses (see a schematic illustration in the inset of Fig.4(c)). The 200 nm spacing is big enough so that the mode coupling between waveguides is negligible. Moreover, 200 nm is also moderate so that sufficiently large number of waveguides can be integrated into the compound plasmonic lens for a reasonable aperture. The thicknesses of these waveguides generally range from 260 nm to 1.8 μm, which are smaller than the electrical field decay length of 3.35 μm at 450 nm [19]. Thanks to the strong dispersive properties of the lens, light with RGB (450 nm, 530 nm, 700 nm) color can be focused to well separated positions, as illustrated in Fig. 4(c). By adjusting the PZP to "on" state, i.e. a π phase shift for green light, and "off" state, i.e. a zero phase shift for blue and red light, the green light can be designed to have the shortest focal length. In a similar way, the green light can also be designed to have the longest focal length by adjusting PZP to "on" state for red light and "off" state for green and blue light, as shown in Fig. 4(d).

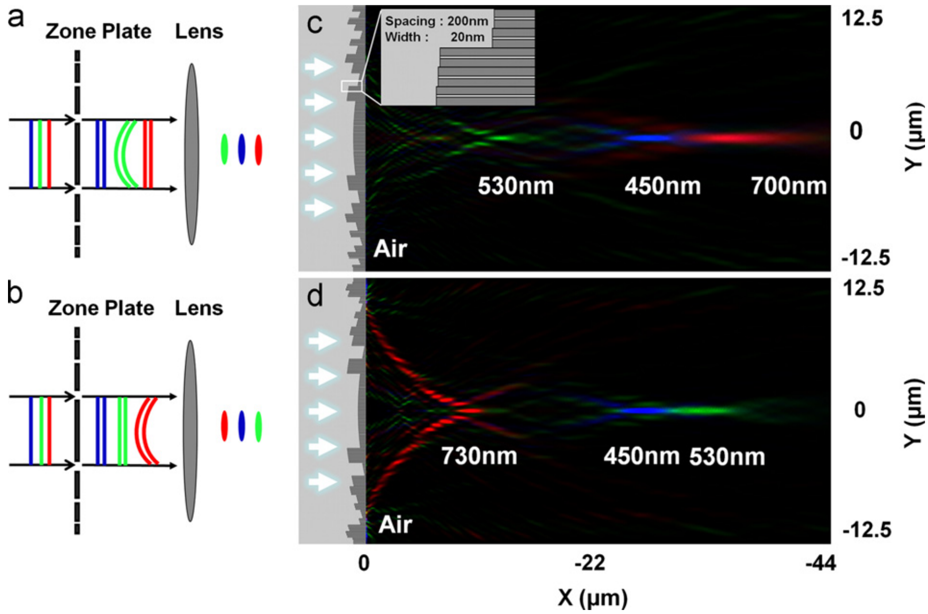

Fig. 4. (a) and (b) The schematics of design principles for compound plasmonic lenses. The distance between the convex lens and the PZP is exaggerated for clarification only. (c) and (d) A practical design of compound plasmonic kinoform lenses with specifically required dispersion properties. These compound plasmonic kinoform lenses are made of exact multiple waveguides with 200 nm spacing and various optimized reduced thicknesses. Green light (530 nm) can be designed to have either the shortest or the longest focal length. The light intensity of each wavelength is normalized to itself. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussions

The transmission efficiency plays an important role in the performance of a plasmonic lens. Since the thicknesses of the multiple waveguides in Fig. 4 vary from 260 nm to 1.8 μm, we calculated the transmittance of the waveguides with different thicknesses, and a few representative curves are shown in Fig. 5(a). The number of the resonant transmission peaks increases with the increasing thickness of the waveguides, indicating the Fabry–Perot resonance nature in the waveguide [5]. Moreover, the transmittance would decrease due to bigger loss induced by the longer propagation length. For light at wavelength of 530 nm, the estimated overall transmission efficiency of the compound kinoform plasmonic lens is about 3.8%, by integrating transmittance of all the individual waveguides. Such energy efficiency however can be significantly enhanced by reducing the period of the waveguides, as shown in Fig. 5(b). When the period changes from 200 nm to 120 nm, the overall lens transmittance increases from 3.8% to 11.6%.

It is worth mentioning that, our designed kinoform lens works not only for three wavelengths but also for three bands. The RGB bands (420–470 nm, 520–535 nm, 630–730 nm) could be well separated and focused. In addition, the widths (± 2 nm) and thicknesses (± 10 nm) of the kinoform plasmonic lens were randomly changed in order to explore the tolerance of the geometry. We found that the RGB light (700 nm, 530 nm, 450 nm) were still well focused with slightly shifted focal positions. Due to the broadband properties and the tolerance of the geometry, the demonstrated properties of the designed kinoform plasmonic lens would remain unchanged even with imperfect fabrication.

Extension of the working spectrum into the ultraviolet or infrared region has no fundamental limitations, although it requires proper materials with carefully designed geometries. Combined with a metamaterial slab, it also has the potential to achieve super resolution [16]. The diffraction efficiency of the

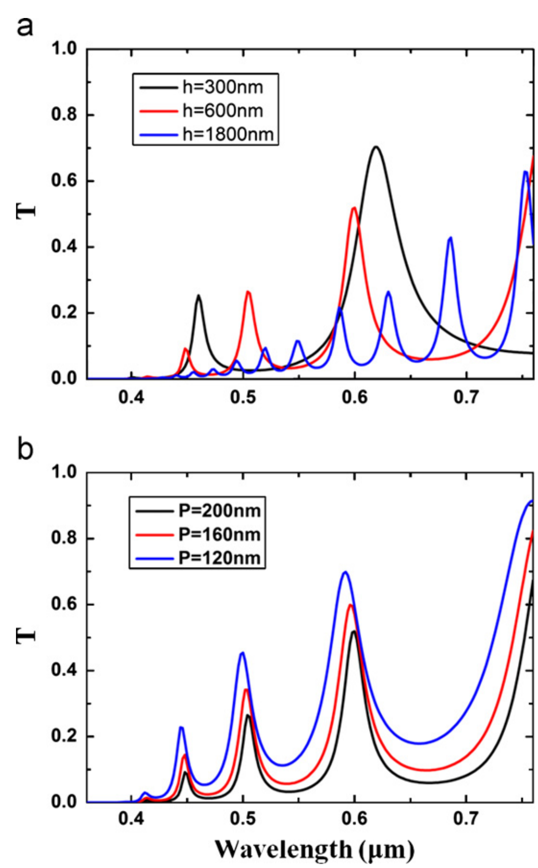

Fig. 5. Calculated energy transmittance of a periodic Ag–air–Ag plasmonic waveguide array. The width of each waveguide is 20 nm. The surrounding media is air and the TM plane wave is assumed to be normal incidence. (a) Different thicknesses of the waveguides with the period of 200 nm. (b) Different periods of the waveguides with the thickness of 600 nm.

diffractive optical elements can be furthermore improved by multi-level phase structures [20]. The controllable dispersive properties of the compound plasmonic lenses present big advantages over those of reflective/refractive optical elements, providing the designing of small volume lenses and important insights into broader applications of diffraction elements in kinoform, binary optics and other holographic optical devices.

5. Conclusion

In summary, we proposed and numerically demonstrated novel compound plasmonic lenses by integrating MIMWG-based lenses with PZPs. Designable dispersive performance of MIMWG-based lens can be realized by selecting proper materials and geometrical parameters. We also analyzed the crucial function of a PZP in the compound plasmonic lens and its wavelength-dependent diffraction efficiency. By tailoring the diffraction efficiencies for different light, it is possible to not only compensate the dispersion over a band of frequencies but also rearrange the focal order of the visible light using this new type of kinoform lens. This compound plasmonic kinoform lens opens a new way to lens dispersion engineering as well as potential applications such as multi-dimensional image sensor, optical excitation and data storage.

Acknowledgments

The authors acknowledge the support of NSF-ECCS under Grant no. 0969405, NSF-CMMI under Grant no. 1120795, the National Basic Research Program of China under Grant no. 2012CB921503 and China Scholarship Council.

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