Achromatic lens based on a nanowire material with anomalous dispersion

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Abstract: Achromatic doublets made of materials with normal dispersion have been used for decades to minimize the effects of chromatic aberrations inherent to single-glass optical lenses. Here, we propose a fundamentally different solution to correct the chromatic aberrations based on a nanowire metamaterial with low loss broadband anomalous dispersion in the visible domain. It is theoretically and numerically shown that the proposed metamaterial lens practically eliminates the chromatic aberrations for all the colors of light, and may be an interesting alternative to conventional achromatic doublets.

OCIS codes: (160.3918) Metamaterials; (220.1000) Aberration compensation; (080.3630) Lenses.

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1. Introduction

Conventional optical single-material glass lenses are unable to focus all the spectral components of light into the same convergence point, even in ideal circumstances where the effects of diffraction are negligible. The reason for this limitation is the frequency dispersion of the glass refractive index, which causes wavelengths associated with different colors to be refracted differently [1]. Hence the image produced by a glass lens may be distorted, and in such a case the optical system is said to suffer from chromatic aberrations. The material dispersion is manifested in the form of beautiful rainbows when white light is separated into its spectral components by a glass prism [2], and is rooted in fundamental physical restrictions, stemming from the causality and passivity of the dielectric response. Causality and passivity determine that the index of refraction of any conventional low loss dielectric material is a strictly increasing function of frequency [3].

Since the optical path length of a given ray in an optical system, $\Psi = n_1 l_1 + ... + n_N l_N$, is written in terms of the indices of refraction (n_i) of the involved materials, the correction of chromatic aberrations is a non-trivial problem. Indeed, the material dispersions are combined additively, and since $\dot{n}_i \equiv dn/d\omega > 0$, it follows that Ψ is a strictly increasing function of frequency. Nevertheless, several strategies to minimize the effect of chromatic aberrations are well documented in the literature and are typically based on the combination of materials with different positive dispersion (e.g [4–7].). This is possible because the system can be designed so that the trajectories of the rays inside the lens change with frequency in such a manner that the profile of Ψ at the exit surface is invariant (apart from the sum of an irrelevant constant). Lenses with reduced aberrations are known as achromatic doublets.

The definition of Ψ suggests that the effects of material dispersion in glass ($\dot{n}_g > 0$) may be easier to suppress if a material with anomalous dispersion ($\dot{n}_{xw} < 0$) is available. However, the aforementioned restrictions stemming from Kramers-Kronig relations for causal and passive dielectric media [3], indicate that a regime of anomalous dispersion implies very significant loss, and hence this solution seems to be impractical. Is it possible to overcome this limitation?

Structured functional materials with extended electromagnetic responses have been on the spotlight in recent years [8–12]. Typically, such metamaterials consist of periodic arrangements of metallic or dielectric particles embedded in a host material. The key feature of metamaterials is that their electromagnetic response is mainly determined by the geometry of the inclusions, rather from the chemical properties of its constituents, allowing for a greater control of their effective response. In particular, it has been shown in a recent work [12] that surprisingly the restrictions on $\dot{n} = dn/d\omega$ coming from Kramers-Kronig relations are less severe for the class of metamaterials with spatial dispersion. Different from conventional dielectrics, spatially dispersive materials are characterized by the fact that the polarization vector responds in a nonlocal manner to the macroscopic electric field [3]. It was shown in Ref [12], that a metamaterial formed by an array of nanowires (a crossed wire mesh) enables a broadband low-loss anomalous dispersion regime, such that $\dot{n}_{xw} < 0$. Here, we theoretically demonstrate that such a metamaterial may permit reducing significantly the chromatic aberration of a conventional thin glass lens.

To begin with, we consider a thin compound lens formed by two materials. The refracting surfaces at the air interfaces have radius of curvature R_1 and R_2. We use the convention that R_1 and R_2 are positive for convex surfaces (seen from the air region), and assume that the *i-th* (*i = 1,2*) refracting material is associated with a material with index $n_i(\omega)$ [see Fig. 1(a)].

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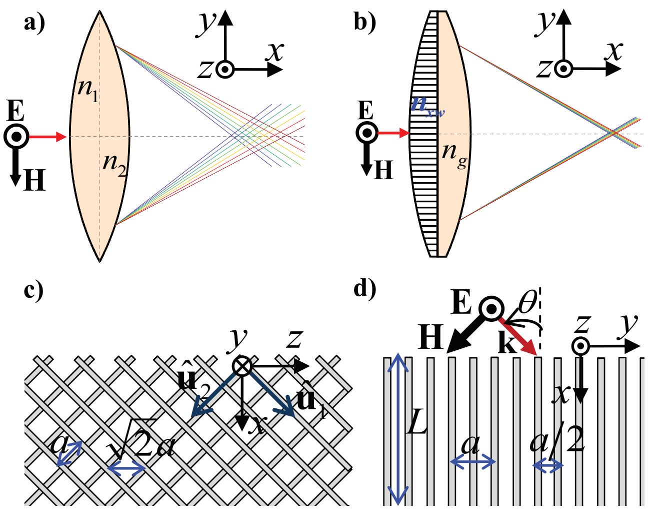

Fig. 1. (a) Illustration of the chromatic aberration of a conventional thin biconvex glass lens with parameters $n_1 = n_2 = n_g(\omega)$. (b) Biconvex optical metamaterial lens that corrects the chromatic aberration for all the colors of light; the compound lens is formed by a thin plano-convex glass lens coated with a thin plano-convex double wire medium. Panels (c) and (d) show cuts of the "double wire medium" slab along the planes *xoz* and *xoy*, respectively. The slab has thickness L.

Since the radii of conventional optical lenses have physical sizes that correspond to tens or even hundreds of wavelengths of the visible spectrum, geometrical optics may be used to describe how light propagates in such optical systems. For a thin compound lens standing in air, the focal length satisfies the well-known Lensmaker's equation [1]:

$$\frac{1}{f} = (n_1 - 1)\frac{1}{R_1} + (n_2 - 1)\frac{1}{R_2}. \tag{1}$$

For a thin lens, the distances S_1 and S_2, from the object and focal plane to the lens, respectively, satisfy $\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$. Obviously, a lens formed by a single material (let's say glass), has focal length such that $\frac{1}{f} = (n_g - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, where $n_g = \sqrt{\varepsilon(\omega)}$ is the refractive index of the glass. Since the permittivity $\varepsilon(\omega)$ of glass is an increasing function of frequency in the optical domain [3], it is manifest from Eq. (1) that the focal length f of the lens is a decreasing function of frequency. Therefore, the focusing provided by the biconvex lens of Fig. 1(a) is imperfect, as the colors of light associated with longer wavelengths ("red" light) are less refracted by the optical system, converging to a longitudinal point farther than the components of light associated with shorter wavelengths ("violet" light). The change δf in the focal length caused by a change Δn_g in the refractive index of the glass is the chromatic aberration.

For a compound lens we may suppose that to a first approximation both n_1 and n_2 vary linearly with frequency so that $n_1 \approx n_{10} + \dot{n}_1(\Delta\omega)$ and $n_2 \approx n_{20} + \dot{n}_2(\Delta\omega)$ where $\dot{n}_1 = dn_1/d\omega$, $\dot{n}_2 = dn_2/d\omega$, $\Delta\omega = \omega - \omega_0$, and that ω_0 is some reference frequency at which

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the lens is designed (and for which $n_1 = n_{10}$ and $n_2 = n_{20}$). Then, using Eq. (1), we easily find that the optical power of the bi-layer lens can be made independent of frequency provided [4]:

$$\dot{n}_1 = -\frac{R_1}{R_2}\dot{n}_2. \quad (2)$$

From the above formula it is manifest that the correction of the chromatic aberrations can be achieved by considering two materials with positive dispersion (when $\dot{n}_1$ and $\dot{n}_2$ are both positive) and such that the radii of curvature of two refracting surfaces have opposite signs. This is the conventional solution that is the basis of achromatic doublets and that has been used for decades [4].

Let us now consider that the thin lens is instead formed by two convex refracting surfaces, i.e. R_1 and R_2 are positive. In such a scenario, in order to satisfy the condition (2) a material with anomalous dispersion is required, because $\dot{n}_1$ and $\dot{n}_2$ must have opposite signs. As far as we know, this solution has not been seriously considered before because regimes of anomalous dispersion in conventional materials imply very significant loss. Here, we show that such a solution is within the realm of reality if the material with anomalous dispersion is taken as a metamaterial with engineered dispersion. For this case we put $n_1 = n_{xw}(\omega)$ and $n_2 = n_g(\omega)$, being $n_{xw}(\omega)$ the effective index of refraction of the metamaterial. Hereafter, a lens that satisfies Eq. (2) with $\dot{n}_{xw} < 0$ will be referred to as *compensated* biconvex lens.

2. Metamaterial with broadband anomalous dispersion

An interesting possibility to realize the required material with anomalous dispersion is the nanowire metamaterial investigated in Ref. [12]. This material is formed at the nanoscopic level by two nonconnected arrays of metallic nanowires, such that each array of parallel wires is arranged in a square lattice with lattice constant a and tilted by $\pm 45^\circ$ with respect to the *x* axis. The two arrays of wires are mutually orthogonal and lie in planes parallel to the *xoz* plane; the distance between adjacent perpendicular wires is $a/2$ [Figs. 1(c) and 1(d)]. For simplicity of modeling, and without loss of generality, it will be assumed that the wires stand in air.

The nanowire metamaterial is characterized by a strong spatial dispersion, i.e, the permittivity seen by a wave with propagation factor $e^{i\mathbf{k}\cdot\mathbf{r}}$ depends on the wave vector $\mathbf{k} = (k_x, k_y, k_z)$ [12]. For propagation in the *xoy* plane with $k_z = 0$ and assuming that the electric field is polarized along the *z* direction, the effective permittivity of this material is [12,13]:

$$\varepsilon_{xw}(\omega, k_x) = 1 + \frac{1}{\left[(\varepsilon_m - 1) f_V\right]^{-1} - \left[(\omega/c)^2 - k_x^2/2\right]/\beta_p^2}, \quad (3)$$

where $\beta_p = \{2\pi/[\ln(a/2\pi r_w) + 0.5275]\}^{1/2}/a$ is the plasma wave number, r_w and ε_m are the radius and the complex permittivity of the metallic wires, respectively, and $f_V = \pi\left(r_w/a\right)^2$ is the volume fraction of each set of wires. The effective index of refraction, $n_{xw} = ck_x/\omega$, of the metamaterial is found by solving the dispersion equation $k_x^2 = \left(\omega/c\right)^2 \varepsilon_{xw}(\omega, k_x)$ with respect to k_x. This yields:

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$$n_{xw} = \sqrt{\frac{3}{2} - \left(\frac{\beta_p c}{\omega}\right)^2 \frac{1}{(\varepsilon_m - 1) f_V} + \sqrt{\frac{1}{4} + \left(2 - \frac{1}{(\varepsilon_m - 1) f_V}\right)\left(\frac{\beta_p c}{\omega}\right)^2 + \frac{1}{(\varepsilon_m - 1)^2 f_V^2}\left(\frac{\beta_p c}{\omega}\right)^4}}. \quad (4)$$

In the particular case of perfectly conducting wires ($\varepsilon_m = -\infty$), the index of refraction reduces to $n_{xw} = \sqrt{\frac{3}{2} + \frac{1}{2}\sqrt{1 + 8\left(\frac{\beta_p c}{\omega}\right)^2}}$, which is clearly a decreasing function of frequency [12], since β_p is a parameter that depends merely on the geometry of the metamaterial. This property still holds for realistic metals at optical frequencies. This is illustrated in Fig. 2(a), where we plot $n_{xw} = n'_{xw} + i n''_{xw}$ as a function of frequency for Al nanowires modeled by a Drude dispersion model with parameters consistent with experimental data reported in the literature [14]. It is seen that the metamaterial is characterized by low-loss broadband anomalous dispersion in the entire visible domain.

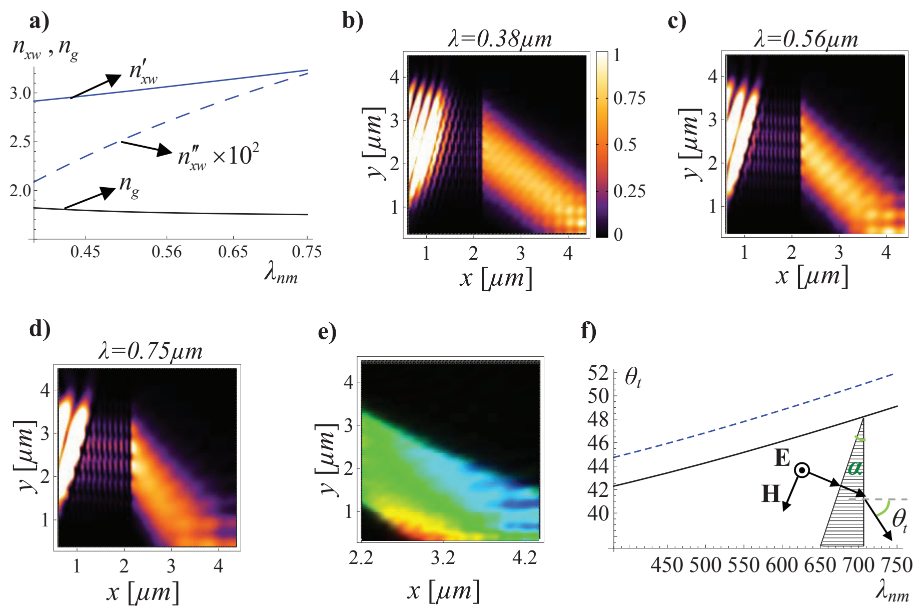

Fig. 2. (a) refractive indices of dense flint glass SF10 (black curve) and of the nanowire metamaterial (blue curves). Panels (b), (c) and (d): normalized $|E_z|^2$ in the vicinity of a metamaterial prism at: (b) $\lambda = 0.38\,\mu m$.(c) $\lambda = 0.56\,\mu m$. (d) $\lambda = 0.75\,\mu m$. (e) reversed rainbow obtained by blending the different light wavelengths [panels (b), (c) and (d)]. (f) transmission angle θ_t as a function of the wavelength $\lambda[\mu m]$ for a Gaussian beam that illuminates the prism along the normal direction. The blue dashed curve was obtained using the theoretical formula $\theta_t = \arcsin(n'_{xw} \sin\alpha)$ and the solid black curve was calculated using a full wave FDFD-SD [18] simulation based on the effective medium model

It is curious to mention that notwithstanding that at the "microscopic level" all the constituents (host and inclusions) of the metamaterial satisfy $\dot{n} > 0$, the effective medium is characterized by $\dot{n}_{xw} < 0$ due to the complex electromagnetic interactions between its different elements. In particular, the optical path length of a wave that transverses a metamaterial slab decreases with frequency, whereas a naïve application of the formula $\Psi = n_1 l_1 + ... + n_N l_N$ (with n_i standing either for the inclusions or for the host) would suggest

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the opposite. This apparent contradiction is explained by the fact that the formula $\Psi = n_1 l_1 + ... + n_N l_N$ is not valid when the distance between the different materials is small on the scale of the wavelength, because in such conditions the wave envelope is described by an effective index of refraction, which is not a simple average of those of the constituent materials. In some sense, in a nanowire metamaterial the sum of many positives ($\sum_i l_i \dot{n}_i > 0$) can yield a negative optical path length ($\dot{n}_{xw} \sum_i l_i < 0$).

To numerically solve the Maxwell's equations in a scenario wherein electromagnetic waves interact with spatially dispersive bodies (using effective medium theory) such as the nanowire metamaterial, we use the finite differences frequency domain (FDFD) method [15]. The FDFD method that we use to characterize spatially dispersive materials (FDFD-SD) is based on ideas analogous to those described in Refs. [16,17], and specific details are reported in Ref [18]. In order to confirm that the effective refractive index of the double wire medium is a decreasing function of frequency in the optical domain, we investigated the refraction of a cylindrical Gaussian beam by a metamaterial prism with $\alpha = 14^\circ$ and aperture $W = 6\lambda_{0.75\mu m}$. The metamaterial has lattice constant $a = 100nm$ and the nanowires have radius $r_w = 0.14a$. The beam waist of the incoming wave was taken equal to $2w_0 = 3.5\lambda_{0.75\mu m}$. Figures 2(b), 2(c) and 2(d) show density plots of $|E_z|^2$ in the vicinity of the prism at $\lambda = 0.38\,\mu m$, $\lambda = 0.56\,\mu m$ and $\lambda = 0.75\,\mu m$, respectively, and support that shorter wavelengths are less refracted than longer wavelengths, confirming that the effective refractive index n_{xw} of the metamaterial prism is a decreasing function of frequency in the optical domain. The spectral electromagnetic fields associated with $\lambda = 0.38\,\mu m$, $\lambda = 0.56\,\mu m$ and $\lambda = 0.75\,\mu m$ [Figs. 2(b), 2(c) and 2(d)] can be blended and represented in a RGB color scale – taking into account the relative intensity of the fields for each wavelength—and this results in a reversed rainbow [Fig. 2(e)]. In Fig. 2(f) the angle of transmission, θ_t, is depicted as a function of frequency calculated with *(i)* our FDFD-SD code (black solid curve) [18] *(ii)* the theoretical formula $\theta_t = \arcsin\left(n'_{xw} \sin\alpha\right)$ (blue dashed curve) [12]. It is seen that the results concur very well.

3. Achromatic biconvex metamaterial lens

To illustrate how the considered metamaterial can, indeed, nearly eliminate the chromatic aberration, we consider the design of a compensated biconvex lens such that $f \sim 7.8\mu$m and $n_1 = n_{xw}$, $n_2 = n_g$. The nanowire material has the same parameters as in the previous example, except that the nanowires diameter is increased to $2r_w = 30nm$. We assume that the dielectric is a dense flint glass SF10. In the visible spectrum, the refractive index $n_g(\omega)$ of this glass is described to a first approximation by the so-called Cauchy's equation $n_g(\lambda_{\mu m}) = A + B/\lambda^2$ with $A = 1.7280$ and $B = 0.01342[\mu m^2]$ [19]. At the central frequency of the visible spectrum ($\omega_0/2\pi$=595[THz]), we can estimate $\dot{n}_{xw} = -0.89\times10^{-3}\left[THz\right]^{-1}$, $\dot{n}_g = 0.18\times10^{-3}\left[THz\right]^{-1}$, $n_{xw0} = 3.01$, and $n_{g0} = 1.78$. Hence, from Eqs. (1) and (2) it follows that the radius of curvature of the first and second interfaces is $R_1 = 46.24\,\mu$m and $R_2 = 9.25\,\mu$m, respectively. The central thickness of the two layers is taken $d_1 = 0.26\,\mu m$ and $d_2 = 1.31\,\mu m$.

To have a reference against which we can compare the performance of the compensated biconvex lens, we consider as well an ordinary single material plano-convex lens ($R_1 = \infty$)

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made exclusively of glass ($n_1 = n_2 = n_g$), and with the same optical power as the compensated lens (i.e. $1/f$ is invariant). This requires that the radius of curvature R_{2s} of the convex surface is taken equal to: $R_{2s} = R_2\left(\left|\frac{\dot{n}_g}{\dot{n}_{xw}}\right|\frac{n_{xw0}-1}{n_{g0}-1}+1\right)^{-1} = 6.09\,\mu m$. The central thickness of the single-material lens is $d_{2s} = 1.31\,\mu m$. Figure 3(a) shows the electric field profile calculated along the mid-plane perpendicular to the single-material lens under the illumination of a cylindrical Gaussian beam. The dashed and solid curves in Fig. 3(a) were obtained using a commercial full-wave electromagnetic simulator [20] and our FDFD code, respectively. The FDFD code predicts that the chromatic aberration δf (defined with respect to the central frequency ω_0) at $\lambda = 0.75\mu m$ and $\lambda = 0.38\mu m$, is $\delta f \approx 0.26[\mu m]$ and $\delta f \approx -0.37[\mu m]$ (Fig. 3(a)), respectively.

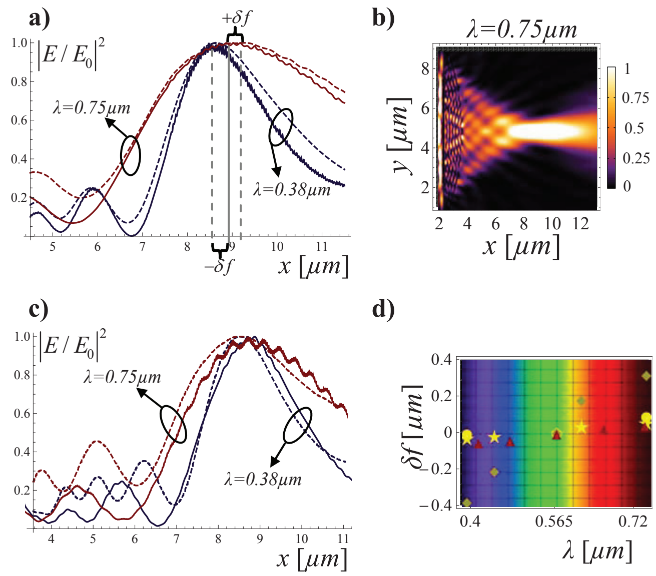

Fig. 3. (a) Profile of the normalized squared electric field near the focal region of the single-material glass lens. Solid curves: obtained using Microwave Studio [20]. Dashed curves: obtained with the FDFD simulator. (b) normalized $|E_z|^2$ (obtained using the FDFD-SD full wave simulator [18]) in the vicinity of the compensated biconvex metamaterial lens. (c) analogous to (a), but for the compensated biconvex metamaterial lens. (d) focal plane curve as a function of the wavelength. The yellow stars (FDFD-SD method based on the effective medium model [18]) and the yellow circles (Microwave Studio [20]) represent the position of the foci of the compensated metamaterial lens. The red triangles and the diamond symbols (FDFD) represent the focal curve of a conventional achromatic doublet and of the single-material lens, respectively.

The achromatic biconvex metamaterial lens performs far better than the ordinary lens. Figure 3(b) shows a density plot of $|E_z|^2$ obtained with the FDFD-SD code at $\lambda = 0.75\mu m$ in the vicinity of the biconvex lens. The focal spot created by the lens under the illumination of a cylindrical Gaussian beam is evident. Figure 3(c) shows the electric field profile calculated along the mid-plane perpendicular to the biconvex lens. For this case, our FDFD-SD code predicts that the chromatic aberration at the wavelength $\lambda = 0.38\mu m$ is drastically reduced to $\delta f \approx 0.052[\mu m]$, whereas the chromatic aberration associated with the wavelength $\lambda = 0.75\mu m$ is reduced to $\delta f \approx -0.039[\mu m]$. Thus, the chromatic aberrations associated with the wavelengths at the edges of the visible spectrum are practically eliminated. This property

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is actually valid in the entire visible spectrum, as supported by Fig. 3(d) that shows the focal curve, .i.e., the chromatic aberration δf as a function of the wavelength. The yellow stars were calculated using the FDFD-SD simulations whereas the yellow circles were obtained using the full wave simulator taking into account all the minute details of the metamaterial [20]. It can be seen that the compensated lens permits focusing all the colors into the same convergence point. The diamond symbols in Fig. 3(d) represent the focal curve of the ordinary single-material glass lens of Fig. 3(a), showing a significant chromatic aberration.

It should be noted that Eq. (1) is based on the thin lens approximation, and thus even within the framework of geometrical optics it is not exact. To take this into account and have a more robust correction of the chromatic aberrations, we have slightly adjusted the parameters of the metamaterial in the FDFD-SD simulations of Fig. 3 so that $a \approx 94nm$ and $2r_w \approx 33nm$. Moreover, in the CST simulations of Fig. 3, the lattice constant of the nanowire material and the diameter of the wires were adjusted to $a \approx 123nm$ and $2r_w \approx 25nm$, in order to have a physical response more consistent with the homogenization model.

We have also investigated the performance of a standard doublet formed by a biconvex crown glass N-BK7 lens [21] and a concave-plane dense flint glass SF10 lens. In this scenario, the doublet is formed by two materials with positive dispersion ($\dot{n}_1$ and $\dot{n}_2$ are both positive). Note that this achromat is not of the same type as that represented in Fig. 1, wherein the middle interface is planar. Indeed, we verified with both ray tracing and full wave simulations that the generic configuration of Fig. 1 is less effective in the correction of the aberrations when both materials have positive dispersion than the solution (based on biconvex and concave-plane layers) reported here. In order that the optical power of the doublet is the same as that of the compensated lens, we chose the radii of curvature of the first and second convex surfaces (N-BK7) $R_1 = 3.10\,\mu\text{m}$ and $R_2 = 9.25\,\mu\text{m}$, and the radius of curvature of the concave-plane surfaces (SF10) $R_3 = -8.11\,\mu\text{m}$ and $R_4 = \infty$.The central thicknesses of both glasses is $1\,\mu m$. The focal curve of this doublet is also represented in Fig. 3(d) (red triangles), showing a reduction of the chromatic aberration comparable to that of the compensated lens.

4. Conclusion

In conclusion, a metamaterial with low-loss broadband anomalous dispersion in the optical domain, may be instrumental in the design of optical systems with performance independent of the material dispersion. The level of aberrations obtained with the design reported in this work is of order of magnitude comparable to what is achievable with conventional achromats. Since by adjusting the composition and geometry of the metamaterial one can engineer the dispersion of n_{xw}, we envision that despite the obvious technological challenges, an optimized structure may provide an exciting route for improved optical instruments insensitive to chromatic aberrations.

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