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Jiajun Chen  
*University of New Orleans*

Cosmin Radu  
*University of New Orleans*

Ashok Puri  
*University of New Orleans*

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Aberration-free negative-refractive-index lens

Jiajun Chen,a) Cosmin Radu,a) and Ashok Puri
Department of Physics, University of New Orleans, New Orleans, Louisiana 70148

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The aberrations of a spherical lens composed of left-handed materials are studied in this letter. Five Seidel aberrations (spherical, coma, astigmatism, field curvature, and distortion) as a function of the refractive index \( n \) and shape factor \( q \) of the lens are considered. Our numerical calculations show that the negative refractive index gives much larger windows of small values of aberrations than the positive index, which will significantly enhance the flexibility for the design of an optical lens. Two possible regions with optimized aberrations are proposed: \( n = -1 \), \( q = -2.2 \) and \( n = -0.81 \) and \( q = 0.83 \). © 2006 American Institute of Physics. [DOI: 10.1063/1.2174087]

Materials with simultaneously negative dielectric permittivity and magnetic permeability are called left-handed materials (LHM), in which the phase velocity of the light wave propagating is pointed in the opposite direction of the energy flow, namely, the Poynting vector is antiparallel to the wave vector. Thus, these materials possess a negative refractive index (NRI). The possibility of the existence of such materials was first pointed out by Veselago.1 The successful fabrication of LHM by using photonic crystals or composite metamaterials has triggered intensive investigation on designing microwave and optical elements.2–9 These engineered composites enable a refractive index less than one or equal to −1, has been studied intensively due to its exceptional focusing ability by which a resolution exceeding diffraction limit is possible. However, it can operate only when the source is close to the lens. But for the practical applications, such as telescopes and microwave communications, focusing distant radiation is needed. In order to focus a farfield radiation, the NRI lens with a concave surface is required. They set the value of \( n \) and the image position, respectively. The spherical aberration maintains a value of 1 when the refractive index deviates from −1. It is important to note that the spherical aberration maintains a value of 1 when the refractive index is in the range of values near 0. This is because total reflection occurs for a large value of \( h \) due to the interface. Schurig et al. recently investigated the five Seidel aberrations of the NRI lens.12

\[
\frac{n_1}{s_0} + \frac{n_2}{s_i} = \frac{n_2 - n_1}{R} + h^2 \left[ \frac{n_1}{2s_0} \frac{1}{s_0^2} + \frac{1}{R^2} \right] + \frac{n_2}{2s_i} \left[ \frac{1}{s_i^2} - \frac{1}{s_i} \right]
\]

(1)

was used, a deviation proportional to \( h^2 \) is measured from the first-order theory,13 where \( s_0 \) and \( s_i \) are the source position and the image position, respectively. The relation between the spherical aberrations and the refractive index is shown in Fig. 2, in which the object distance \( s_i \) is assumed to be 1 and the maximum distance above the axis, \( h \), is 0.1, 0.4, and 0.8, respectively. The spherical aberration is observed when the refractive index deviates from −1. It is important to note that the spherical aberration maintains a value of 1 when the refractive index is in the range of values near 0. This is because total reflection occurs for a large value of \( h \) due to the interface.

![FIG. 1. Basic configuration for spherical aberration calculation. As the diameter of the spherical surface approaches infinity, \( n_1 = 1 \) and \( n_2 = -1 \), a "perfect lens" is constructed.](image-url)
and point on the optical axis, the deviation from ideal spherical converges to an ideal point focus in ray optics. For an object corrections to the simple Gaussian optical formulas are cal-
erations: spherical, coma, astigmatism, field curvature, and distortion. They can be written by the refractive index (n), the position factor (p), the shape factor (q), and the focal length (f’), the definitions of which were given by Mahajan. For most applications in reality, such as telescopes and microwave communications, we would like to focus the radiation from the object at infinite position. In this case, p = -1 and f’ = 1, and the five coefficients are the function of refractive index n and the shape factor q:

\[ C_{040} = -\frac{n^3 + (n-1)^2(3n+2) - 4(n+1)(n-1)q + (n+2)q^2}{32n(n-1)^2}, \]
\[ C_{131} = \frac{(2n+1)(n-1) - (n+1)q}{4n(n-1)}, \]
\[ C_{222} = -\frac{1}{2}, \]
\[ C_{220} = -\frac{(n+1)}{4n}, \]
\[ C_{311} = 0. \]

The astigmatism and distortion are independent of the refractive index and the shape factor and maintain values of -0.5 and 0, respectively. Field curvature \( C_{220} \) is independent of the shape factor of the lens, and only when \( n = -1 \), the field curvature is zero. It is impossible to eliminate field curvature when \( n \) is positive. Furthermore, the field curvature goes to infinity when \( n = 0 \). Schurig et al. bent the lens (change shape factor) to eliminate one aberration and evaluate the others. If coma \( C_{131} \) is zero, the shape factor is given by \( q = (2n+1)/(n-1) \). And this will cause the spherical aberration goes to infinity for \( n = -1 \). For a lens with zero spherical aberration, the shape factor can be written by

\[ q = \frac{4n^2 - 4 \pm 2\sqrt{n^2 - 4n^3}}{2(n+2)}, \]

which requires \( n \leq 1/4 \). This means it is impossible to eliminate spherical aberration when \( n > 1/4 \). Thus, the spherical aberration and curvature can be eliminated simultaneously with a relatively small coma \( C_{131} = 0.25 \) when \( n = -1 \), and \( q = \pm \sqrt{5} \). However, these analyses do not examine all the situations with respect to different shape factors \( q \) and refractive indexes \( n \), respectively. In order to evaluate all the possible situations and balance these aberrations, we numeri-

\[ \text{Aberration}(Q) = cp^4 - cb^4. \]
cally calculate the dependence of the aberration coefficients on the shape factor and the refractive index, namely, we expand our evaluation of aberrations to the $n-q$ plane. The results for the spherical aberration, coma, and curvature are shown in Figs. 4(a)–4(c) in a color-coded scheme. For all of these aberrations, the negative index gives much larger windows of small aberrations (navy blue areas) than those given by the positive refractive index. A better method to minimize the aberrations simultaneously is to evaluate the dependence of the sum of the absolute values of aberrations, $C_{\text{total}} = |C_{040}| + |C_{131}| + |C_{220}|$, on the parameters $(q$ and $n)$. The values of $C_{\text{total}}$ with respect to $q$ and $n$ are plotted in Fig. 4(d). Not surprisingly, the negative refractive index has a much larger window of small aberrations. This asymmetry implies much more flexibility of the lens design by using the negative refractive index. The detailed contour map of the areas with small aberrations is also plotted in Fig. 5. We should concentrate on small absolute values of index, because a large index will yield strong reflection due to the impedance mismatch. The numerical results show that there are two minimum values of $C_{\text{total}}$ with a small absolute index: $C_{\text{total}} = 0.25$ (n = −1, q = −2.2) and $C_{\text{total}} = 0.22$ (n = −0.81, q = 0.83). As q = −2.2 and n = −1, the three aberrations are optimized: $C_{040}$ = −0.0001, $C_{131}$ = 0.25, $C_{220}$ = 0, which is corresponding to the analytical result shown before. The situation that n = −0.81, q = 0.83 is another possible selection for optimizing $C_{\text{total}}$, for which $C_{040}$ = 0.0004, $C_{131}$ = 0.1644, and $C_{220}$ = 0.0586. Thus, q = −2.2 implies curvature ratio $R_1/R_2 = (q−1)/(q+1) = 2.7$ (concavo-convex), and q = 0.83 gives $R_1/R_2 = −0.93$ (a biconcave or biconvex lens).

In summary, the Seidel aberrations, including spherical, coma, astigmatism, field curvature, and distortion, are investigated for the lens with a negative refractive index. The numerical calculation results show that the negative refractive index gives much larger windows of small values of aberrations, which will significantly enhance the design flexibility of an optical lens. Two possible areas with minimized aberrations are proposed: n = −1, q = −2.2 and n = −0.81 and q = 0.83.

FIG. 4. (Color) Numerical calculated coefficients of the spherical aberration $C_{040}$ (a), coma $C_{131}$ (b), curvature $C_{220}$ (c), and the sum of the three aberrations $|C_{040}| + |C_{131}| + |C_{220}|$ (d) as a function of the shape factor $q$ and refractive index $n$. The values of the color bars for the spherical aberration, coma, and field curvature range from 0 (navy blue) to 1 (garnet), and the value for the sum spans from 0 to 3.

FIG. 5. (Color) Detailed contour map of the area with small values of the sum of the three aberrations $C_{\text{total}} = |C_{040}| + |C_{131}| + |C_{220}|$. There are two minimums near the small refractive index area ($|n| < 2$): $C_{\text{total}}$ = 0.22 for n = −0.81 and q = 0.83; $C_{\text{total}}$ = 0.25 for n = −1 and q = −2.2. In order to give the details, the range of the color bar is shrunk to the values from 0.2 to 0.6.