Scaling slabs based on transformation optics for immersion lenses and angular filters

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Abstract

We discuss two applications of compressing/expanding slabs based on transformation optics. The first one is an immersion lens that, unlike conventional ones, is flat, reflectionless, and does not distort the image when the source is not at its centre. The second application is a spatial filter whose response is a scaled version (in angle) of that of an infinite dielectric slab.

1. Introduction

Recently, it has been shown that squeezers based on transformation optics are reflectionless for TE waves if the output medium is a dielectric with a refractive index equal to the compression factor [1]. Following a similar reasoning, it can be proven that an expanding device is reflectionless if the medium to be expanded has a refractive index equal to the expansion factor and the output medium is free space. In this work, we use this property to design a flat and reflectionless immersion lens and a spatial filter with some interesting properties. Specifically, the filter reflection coefficient $R_F(k_x)$, where k_x is the transverse component of the wave-vector of impinging light, is similar to that of an infinite dielectric slab $R_S(k_x)$, but after a scaling in k_x by a constant factor F. Although under certain conditions squeezers/expanders can be reflectionless for TM waves as well, here we will limit ourselves to a two-dimensional problem (with coordinates x and z, being z the propagation direction) for TE waves.

2. Flat reflectionless immersion lens

An immersion lens made up of a dielectric medium with refractive index n can improve the diffraction limited resolution of free space by a factor of $1/n$ [2]. The usual geometry of an immersion lens is that of a hemisphere, although other curved surfaces can be used. Thus, one side of the system is flat, while the other one is curved. For some applications, it would be desirable that both surfaces were flat. In addition, there appear reflections at the boundary of the lens with free space due to the difference in the refractive indices of both media. We would like to overcome both drawbacks. Basically, we want to reconstruct with our far-field optical system a certain electromagnetic field distribution in vacuum, for instance in the plane $z = 0$, far away (in terms of wavelength) from the optical system. The spatial resolution of our system will be limited to approximately the wavelength of operation λ. However, if the whole system were immersed in a dielectric medium with refractive index n_1, the limiting resolution would be λ/n_1. We would like to transfer this higher resolution power of the dielectric medium to free space so that we can use our external optical system to produce an image with such resolution. Let us consider two different cases. In the first one we have a certain distribution $U_1(x, z = 0)$ in free space. In the second case, we have a distribution $U_2(x, z = 0)$ in a dielectric medium with index n_1, which is a compressed version of U_1 such that $U_2(x, z = 0) = U_1(n_1x, z = 0)$. We can use the angular spectrum decomposition to express the field distribution in any z-plane as a superposition of plane waves [3]:

$$A\left(\frac{\alpha}{\lambda},z\right)=\int_{-\infty}^{\infty}U\left(x,z\right)e^{-i2\pi\frac{\alpha}{\lambda}x}dx \qquad U\left(x,z\right)=\int_{-\infty}^{\infty}A\left(\frac{\alpha}{\lambda},z\right)e^{i2\pi\frac{\alpha}{\lambda}x}d\frac{\alpha}{\lambda} \tag{1}$$

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At a certain distance $z = d$, the disturbance in Fourier space will be given by [3]:

$$A\left(\frac{\alpha}{\lambda},z\right)=A\left(\frac{\alpha}{\lambda},0\right)e^{i\frac{2\pi}{\lambda}\sqrt{1-\alpha^2}d} \tag{2}$$

With the help of (1-2), it can be deduced that $U_2(x,d/n_1) = U_1(n_1x,d)$. If we could stretch the fields $U_2(x,d/n_1)$ that we have in our dielectric medium by a factor of n_1, they would be equal to those resulting from the propagation of a distance d of the disturbance U_1 in free space. Transformation optics provides a way to design the required medium to achieve this field deformation and obtain $U_2(x/n_1,d/n_1)$ from $U_2(x,d/n_1)$. Moreover, since the expansion factor is n_1, the device is reflectionless. Therefore, the idea is as follows. We have a certain electromagnetic field distribution that we want to image in the far field with a resolution of λ/n_1. For instance, two illuminated punctual objects separated by a distance of λ/n_1 in the x-direction. We embed this object in (or put this object very near from) a medium with a refractive index of n_1, where the limiting resolution is λ/n_1. Now we modify a section of this medium, which will be adjacent to air, in order to expand the fields by a factor of n_1 at a distance $z = d_1/n_1$ away from the source. We cut the modified dielectric medium exactly at this point $z = d_1/n_1$, where we have the expanded fields, leaving free space on the right side of the device. We know that there will be no reflections at this interface, since we used the adequate expanding factor. Thus, the fields exiting the device are the same as those that two punctual sources in free space separated by a distance of λ would generate. This way, we can obtain a magnified image (with a magnification factor n_1) of the two original sources with our optical system, whose resolution is limited to λ. This magnifying lens is flat and reflectionless. To verify our theoretical predictions, we performed some numerical calculations with COMSOL Multiphysics. Specifically, we designed a lens with a magnifying factor $n_1 = 3$. The free space wavelength is $\lambda = 1.5$ µm. To test the device, two sources separated by $\lambda/2$ are placed inside a medium with n_1. When the fields radiated by these sources directly exit to air [Fig. 2(a)], reflections appear. In addition, the radiation pattern in air is that of two sources separated by $\lambda/2$. When we use the magnifying lens between the medium with $n_1 = 3$ and air, no reflections appear and the radiation pattern is that of two sources separated by 1.5λ [Fig 2(b)].

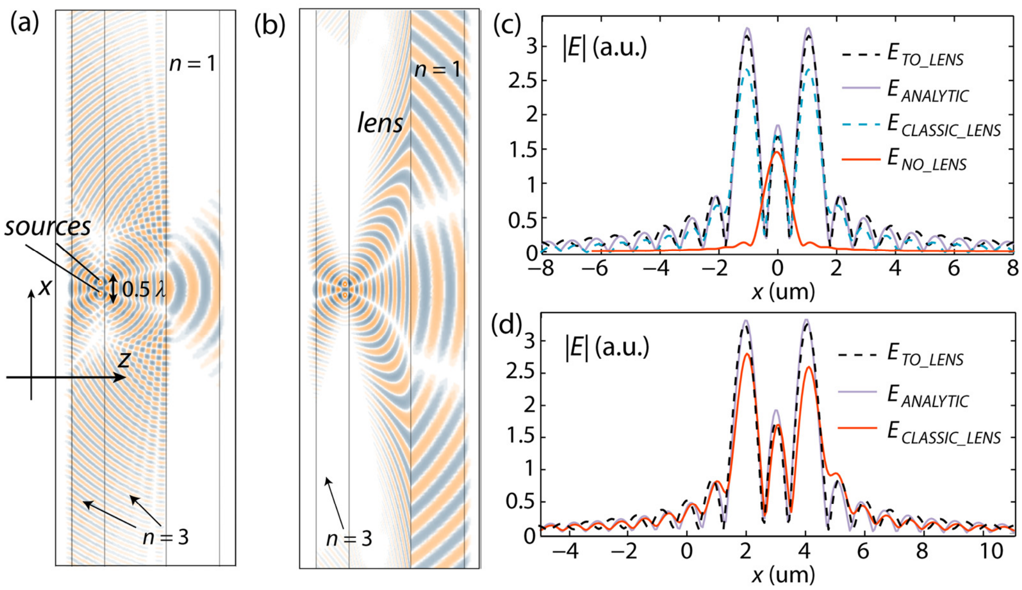

Fig. 1. Electromagnetic field distribution corresponding to two sources embedded in a dielectric with $n = 3$ (a) without and (b) with the designed lens between the dielectric and air ($n = 1$). (c) Reconstructed field amplitude for different cases. (d) Same as in (c) but with the sources 1 µm away from the lens centre.

By using the Fourier inverse filter corresponding to free space for propagating waves, we can reconstruct the distribution in the object plane (z = 0) from numerical calculations for the cases with and without lens (E_{TO_LENS} and E_{NO_LENS}, respectively), in the same way that our external optical system would do [Fig. 2(c)]. In the first case the two sources can be clearly observed while in the second one, some components are lost and we only detect a broad unique source. Note that in the image obtained with the lens there is a magnification factor of 3. This would be equivalent to having the two sources in air and separated by a distance of 1.5λ. We verified this by comparing the reconstructed image from the analytically calculated fields radiated by two sources separated by 1.5λ ($E_{ANALYTIC}$) with E_{TO_LENS}, observing an excellent agreement. We also include the fields we would reconstruct if we used a classical hemi-spherical immersion lens ($E_{CLASSIC\_LENS}$), whose amplitude is lower than the fields recovered when using the proposed lens due to reflections. Finally, we show the effect of separating the sources from the lens origin [Fig. 2(d)]. Clearly, this does not affect the performance of the lens based on transformation optics, while the classical lens introduces some distortion.

3. Angular filters

Consider an air slab in which a compression is performed, so that the compression factor at its output is F. According to our previous considerations, the output of the slab is matched to a dielectric with refractive index $n = F$. Now, imagine that we leave empty space to the right of $z = d$. In this case, we will have a reflection coefficient $R_S(k_x)$ at $z = d$ equal to that between air and a dielectric with $n = F$. The continuity of the transformation guarantees that there will be no reflections at $z = 0$. Thus, an incident electromagnetic distribution $U(k_x)$ will enter the slab and propagate until $z = d$. There, we will have a spatially compressed version of $U(k_x)$ (expanded in k_x) multiplied by a phase factor due to propagation inside the slab, *i.e.*, $U(k_x/F)\cdot exp(\mathrm{i}(k^2\text{-}(k_x/F)^2)^{1/2}d)$. Part of this field is reflected so we have a wave propagating to the left in $z = d$ of the form $U(k_x/F)\cdot exp(\mathrm{i}(k^2\text{-}(k_x/F)^2)^{1/2}d)\cdot R_S(k_x)$. This wave is spatially expanded as it approaches $z = 0$ so that when exiting the slab we have an expanded version of it (compressed in k_x) times another phase factor, *i.e.*, $U(k_x)\cdot exp(\mathrm{i}(k^2\text{-}k_x^2)^{1/2}d)\cdot R_S(Fk_x)\cdot exp(\mathrm{i}(k^2\text{-}k_x^2)^{1/2}d)$. Since there are no reflections at $z = 0$, division by $U(k_x)$ gives the filter reflection coefficient $R_F(k_x)$, which apart from some phase factors is that of the interface (air)-(dielectric with $n = F$) scaled in k_x.

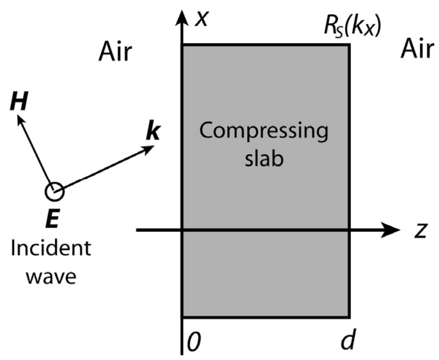

Fig. 2. Spatial filter that uses a scaling slab based on transformation optics

4. Conclusion

We have discussed two applications of scaling slabs based on transformation optics. The first one is a flat reflectionless immersion lens that introduces no distorsions. The second one is a spatial filter that has an exotic reflection coefficient. We will address ways of implementing these elements and more complex filters based on the proposed one. Financial support by Spanish MICINN (contract CSD2008-00066), grant programs of MICINN, UPV, and Generalitat Valenciana are acknowledged.

References

[1] C. García-Meca, M. M. Tung, J. V. Galán, R. Ortuño, F. J. Rodríguez-Fortuño, J. Martí, and A. Martínez, Squeezing and expanding light without reflections via transformation optics, *Opt. Express*, vol. 19, p. 3562, 2011.

[2] S. M. Mansfield and G. S. Kino, Solid immersion microscope, *Appl. Phys. Lett.*, vol. 57, p. 2615, 1990.

[3] J. W. Goodman, *Introduction to Fourier Optics* 2nd edition, McGraw-Hill, 1996.