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Experimental observation of the trapped rainbow

Vera N. Smolyaninova,[1,a)] Igor I. Smolyaninov,[2] Alexander V. Kildishev,[3] and Vladimir M. Shalaev[3]
[1]*Department of Physics, Astronomy, and Geosciences, Towson University, 8000 York Rd., Towson, Maryland 21252, USA*
[2]*Department of Electrical and Computer Engineering, University of Maryland, College Park, Maryland 20742, USA*
[3]*Birck Nanotechnology Centre, School of Electrical and Computer Engineering, Purdue University, Indiana 47907, USA*

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We report on the experimental demonstration of the broadband "trapped rainbow" in the visible frequency range using an adiabatically tapered optical nano waveguide. Being a distinct case of the slow light phenomenon, the trapped rainbow effect could be applied to optical computing and signal processing, such as spectroscopy on a chip, and to providing enhanced light-matter interactions. © *2010 American Institute of Physics*. [doi:10.1063/1.3442501]

The concept of a "trapped rainbow" has attracted considerable recent attention. According to various theoretical models, a specially designed metamaterial[1] or plasmonic[2,3] waveguide has the ability to slow down and stop light of different wavelengths at different spatial locations along the waveguide, which is extremely attractive for such applications as spectroscopy on a chip. In addition, being a special case of the slow light phenomenon,[4] the trapped rainbow effect may be used in applications such as optical signal processing and enhanced light-matter interactions.[5] On the other hand, unlike the typical slow light schemes, the proposed theoretical trapped rainbow arrangements are extremely broadband, and can trap a true rainbow ranging from violet to red in the visible spectrum. Unfortunately, due to the necessity of complicated nanofabrication and the difficulty of producing broadband metamaterials, the trapped rainbow schemes had until recently remained in the theoretical domain only.

In this communication we demonstrate an experimental realization of the broadband trapped rainbow effect which spans the 457–633 nm range of the visible spectrum. Similar to our recent demonstration of broadband cloaking,[6] the metamaterial properties necessary for device fabrication were emulated using an adiabatically tapered optical nano waveguide geometry. A 4.5 mm diameter double convex glass lens was coated on one side with a 30 nm gold film. The lens was placed with the gold-coated side down on top of a flat glass slide coated with a 70-nm gold film [Fig. 1(a)]. The air gap between these surfaces has been used as an adiabatically changing optical nanowaveguide. The dispersion law of light in such a waveguide is

$$\frac{\omega^2}{c^2} = k_r^2 + \frac{k_\phi^2}{r^2} + \frac{\pi^2 l^2}{d(r)^2}, \qquad (1)$$

where $l=1,2,3,\ldots$, etc. is the transverse mode number, and $d(r)$ is the air gap, which is a function of radial coordinate r. Light from a multi-wavelength argon ion laser (operating at $\lambda=457$, 465, 476, 488, and 514 nm) and 633 nm light from a He–Ne laser were coupled to the waveguide via side illumination. This multiline illumination produced the appearance of white light illuminating the waveguide [Fig. 1(b)]. Light propagation through the nano waveguide was imaged from the top using an optical microscope [Fig. 1(c)]. Since the waveguide width at the entrance point is large, the air gap waveguide starts as a multi-mode waveguide. Note that a photon launched into the lth mode of the waveguide stays in this mode as long as d changes adiabatically.[7] In addition, the angular momentum of the photons $k_\phi=\rho k=L$ is conserved (where ρ is the impact parameter defined with respect to the origin). Gradual tapering of the waveguide leads to mode number reduction: similar to our observation of broadband cloaking (described in detail in Ref. 6) only $L=0$ modes may reach the vicinity of the point of contact between the gold-coated spherical and planar surfaces, and the group velocity of these modes

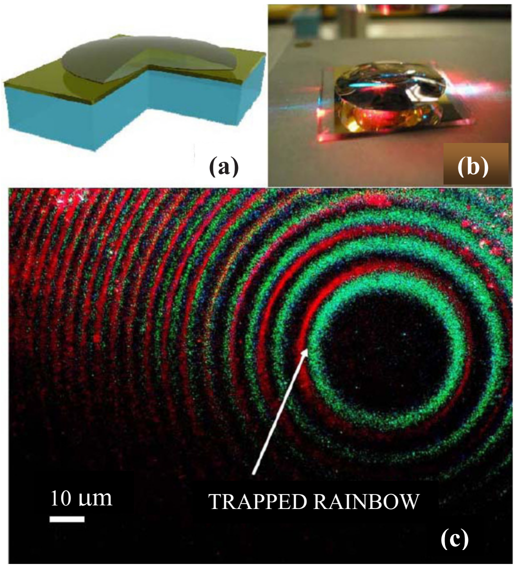

FIG. 1. (Color online) (a) Experimental geometry of the trapped rainbow experiment: a glass lens was coated on one side with a gold film. The lens was placed with the gold-coated side down on top of a flat glass slide also coated with a gold film. The air gap between these surfaces formed an adiabatically changing optical nano waveguide. (b) Photo of the trapped rainbow experiment: HeNe and Ar:Ion laser light is coupled into the waveguide. (c) Optical microscope image of the trapped rainbow.

[a)] Electronic mail: vsmolyaninova@towson.edu. Tel.: 410-704-2608.

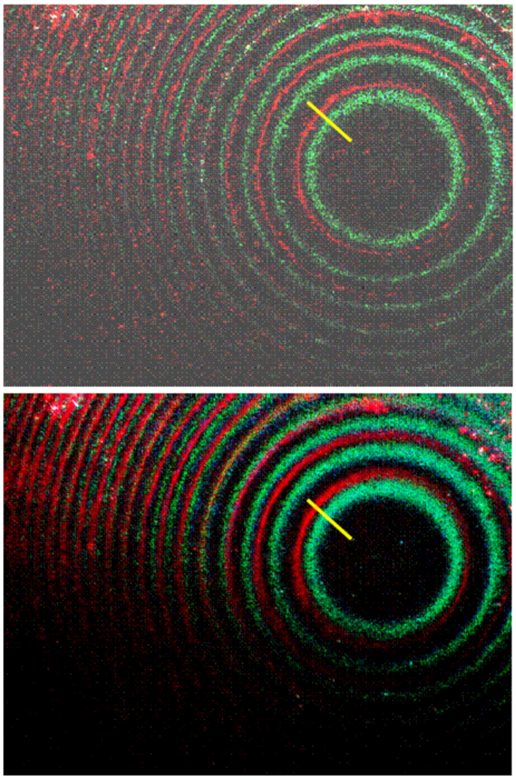

FIG. 2. (Color online) Comparison of the optical microscope images of the trapped rainbow effect from Fig. 1(c) (bottom) and the image (top) obtained when only two laser wavelengths (514 and 633 nm) are used for illumination. Individual spectral lines separated by only a few micrometers appear to be well resolved (see Fig. 3).

$$c_{gr} = c\sqrt{1-\left(\frac{l\lambda}{2d}\right)^2}, \tag{2}$$

tends to zero as d is reduced: the colored rings around the central circular dark area in Fig. 1(c) each represent a location where the group velocity of the lth waveguide mode becomes zero. These locations are defined by

$$r_l = \sqrt{(l+1/2)R\lambda}, \tag{3}$$

where R is the lens radius.[6] Finally, the light in the waveguide is completely stopped at a distance

$$r = \sqrt{R\lambda/2}, \tag{4}$$

from the point of contact between the gold-coated surfaces, where the optical nano waveguide width reaches $d=\lambda/2$ ~ 200 nm range. The group velocity of the only remaining waveguide mode at this point is zero. This is consistent with the fact that the area around the point of contact appears dark in Fig. 1(c). In this area the waveguide width falls below 200 nm down to zero. Since the stop radius depends on the light wavelength, different light colors stop at different locations inside the waveguide, which is quite obvious from Fig. 1(c). Thus, the visible light rainbow has been stopped and "trapped." This observation constitutes an experimental demonstration of a broadband trapped rainbow effect in the visible frequency range. Unlike recently described observation of the trapped rainbow in a left-handed heterostructure,[8] the proposed geometries for trapping light in plasmonic waveguides,[9] and controllable optical "black holes,"[10] our geometry is easily scalable to any spectral range of interest. While the group velocity of the trapped photons is exactly zero at $r=\sqrt{R\lambda/2}$ [see Eq. (2)], light cannot be "stored" indefinitely at these locations due to Joule losses in metal. In the best case scenario photons can be stored for no longer that 100–1000 periods. However, even this duration is enough to cause considerable enhancement of light-matter interaction in this geometry. Note that the light is stopped only for the waveguide mode, which has both the mode number $l=0$ and the angular momentum number $L=0$. Therefore, our current result does not contradict our observations of cloaking reported in Ref. 6. In the ray optics approximation this condition corresponds to the central ray hitting the cloak. As was noted in Ref. 11, such a ray "does not know" which way to turn around the cloak.

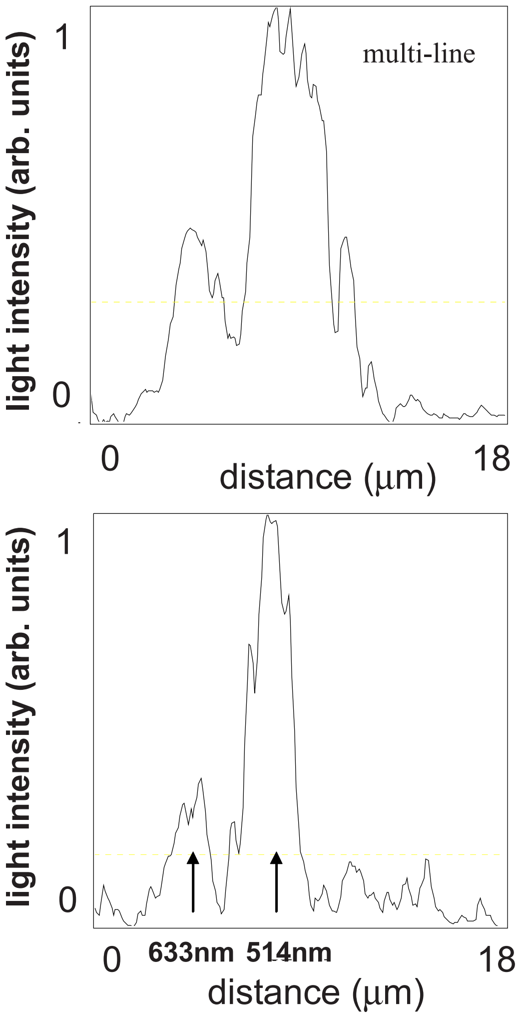

FIG. 3. (Color online) Cross sections of the optical microscope images along the yellow lines shown in Fig. 2. The zero point of the cross sections starts outside the innermost red ring in Fig. 2. Individual spectral lines are clearly resolved in the bottom plot obtained using 514 and 633 nm illumination. Multiple spectral lines are visible in the top cross section.

The described experimental arrangement may be used in such important applications as spectroscopy on a chip. Figure 2 presents a comparison of the optical microscope images of the trapped rainbow effect from Fig. 1(c) and the image obtained when only two laser wavelengths (514 and 633 nm) are used for illumination (shown at the top of Fig. 2). Individual spectral lines separated by only a few micrometers appear to be well resolved in the latter image, which is evident from the cross section analysis presented in Fig. 3. Based on the image cross section analysis, spectral resolution of the order of 40 nm has been obtained. Further improvement of spectral resolution may be achieved by using a gold-coated spherical surface with a larger radius of curvature.

In conclusion, we have reported experimental demonstration of the broadband "trapped rainbow" in the visible frequency range using an adiabatically tapered optical nano waveguide, and gave an example of its potential use in spectroscopy on a chip application. Being a distinct case of the slow light phenomenon, the trapped rainbow effect could be applied to optical computing and signal processing, and to providing enhanced light-matter interactions

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