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Short Communication

Coherent rainbows from solids

Tian-Jiao Sun [a,b,1], Xuan Qian [a,b,1], Ya-Xuan Shang [a,b], Jian Liu [a,b], Kai-You Wang [a,b], Yang Ji [a,b,*]

[a] *State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China*

[b] *College of Materials Science and Opto-Electronic Technology, College of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

Rainbow is an incoherent sum of sunlight refracted by many water droplets and often appears after rain in summer. Since the refraction index of water depends on the light wavelength (i.e., the color), white light goes in and rainbow comes out. The famous Newton's rings are coherent sum of light passing through a lens on a plane glass, showing Newton's color under white light illuminations [1]. Using single-color laser source, coherent rings were first observed in liquid crystal about 37 years ago [2], in solutions of 2,9,16,23-Tetrakis(phenylthio)-29H,31H-phthalocyanine about 15 years ago [3], in liquid suspensions of nano-materials [4–13] and even in Bromocresol purple (BCP): PMMA films [14] in the last decade. Recently, similar diffraction rings were observed in alcohol [15], water and many other liquids [16]. There are ongoing debates on their mechanisms, either an electronic third-order nonlinear self-phase modulation [5] or a thermal lens effect [11]. Here we report the observation of coherent rainbows in many solids and reveal the underlying mechanism.

Focus a beam of white light into colored glass (Fig. 1a), many colorful rings come out like rainbows, as shown in Fig. 1b. We call such interference patterns as coherent rainbows. The white light comes from a pulsed fiber laser with wavelength 0.4–2.0 μm, pulse width ~100 ps, repeating frequency 2 MHz and maximum power ~2 W. The size of the laser focal spot is about 30 μm. When the laser power is about 1.4 W, the coherent rainbows start to appear. This interference pattern is similar to those observed in liquid [2–13]. However, it is totally different from that of Newton's rings: it is much larger, with an outgoing angle of about 10°; it is more compact in the center, while being sparser in the case of Newton's rings.

We also studied many other solids, such as plastics, wax and ice. They all exhibit coherent rainbows (Fig. 1c, d, e). AL-Ahmad et al. [14] also observed similar rings in BCP: PMMA films and ascribed them to the large third-order nonlinear refractive index of the material. If this is the physics behind coherent rainbows, their appearance should be strongly material-dependent. However, this contradicts to what we observed.

To find out the underlying physics of the coherent rainbows, we first investigated the power intensity dependence of the coherent rainbows. The white laser was sent into the colored glass. The laser power was increased smoothly from zero to maximum in about 30 s, then decreased to zero in about 20 s. At the beginning, only one bright spot was seen. When the laser power was above a threshold (about 1.4 W), colorful rings appeared. With increasing the power further, more colorful rings expanded from the center (Fig. 1f, the biggest power is 1.9 W). Then, we reduced the laser power, the rings shrank and the number of rings became less until another threshold (1.6 W). After that, the rings stayed unchanged except being darker and darker (Fig. 1g, also see Movie S1 in the Supplementary data). This behavior rules out the explanation of the thermal lens effect [11].

The surface morphology of the materials was modified (Fig. 2a), when the laser power was above certain value. This happens because the white laser heats the solid locally. The Gauss-like depth profile of the surface morphology (Fig. 2b) will generate an optical-path difference ($L = \int n\mathrm{d}l$, where n is the refraction index) for the light interference. When the outgoing angle ($\Phi = 2\mathrm{d}h/\mathrm{d}r$ for the reflection mode) is smaller than its maximum value $\Phi < \Phi_{\max}$, there are two sub-beams going into the same direction (Fig. 2c). They interfere constructively (or destructively) if $(L_1 - L_2)/\lambda = 2k\pi$ or $(2k-1)\pi$, where k is an integer. The optical-path difference in the reflection mode can be derived analytically (see Fig. S1 in the Supplementary data). With parameters retrieved from the step profiler of Fig. 2b, the simulated results are very similar to the observed rings (Fig. 2d, e).

Coherent rainbows are not from the nonlinear optical effect [14], since a cw He-Ne laser can also create rings if it is set colinearly with the pulsed white laser (see Fig. S2 in the Supplementary data). They are not due to self-phase modulation [5] either, because it also appears in pure liquids [15,16], plastics and ice, which have no mobile electrons.

Interestingly, the familiar optical glass like mirrors and lenses do not show coherent rainbows in the accessible power range of our lab. It is likely due to its high purity and much less absorption of light, thus supporting further our explanation.

* Corresponding author.
E-mail address: jiyang@semi.ac.cn (Y. Ji).

[1] These authors contributed equally to this work.

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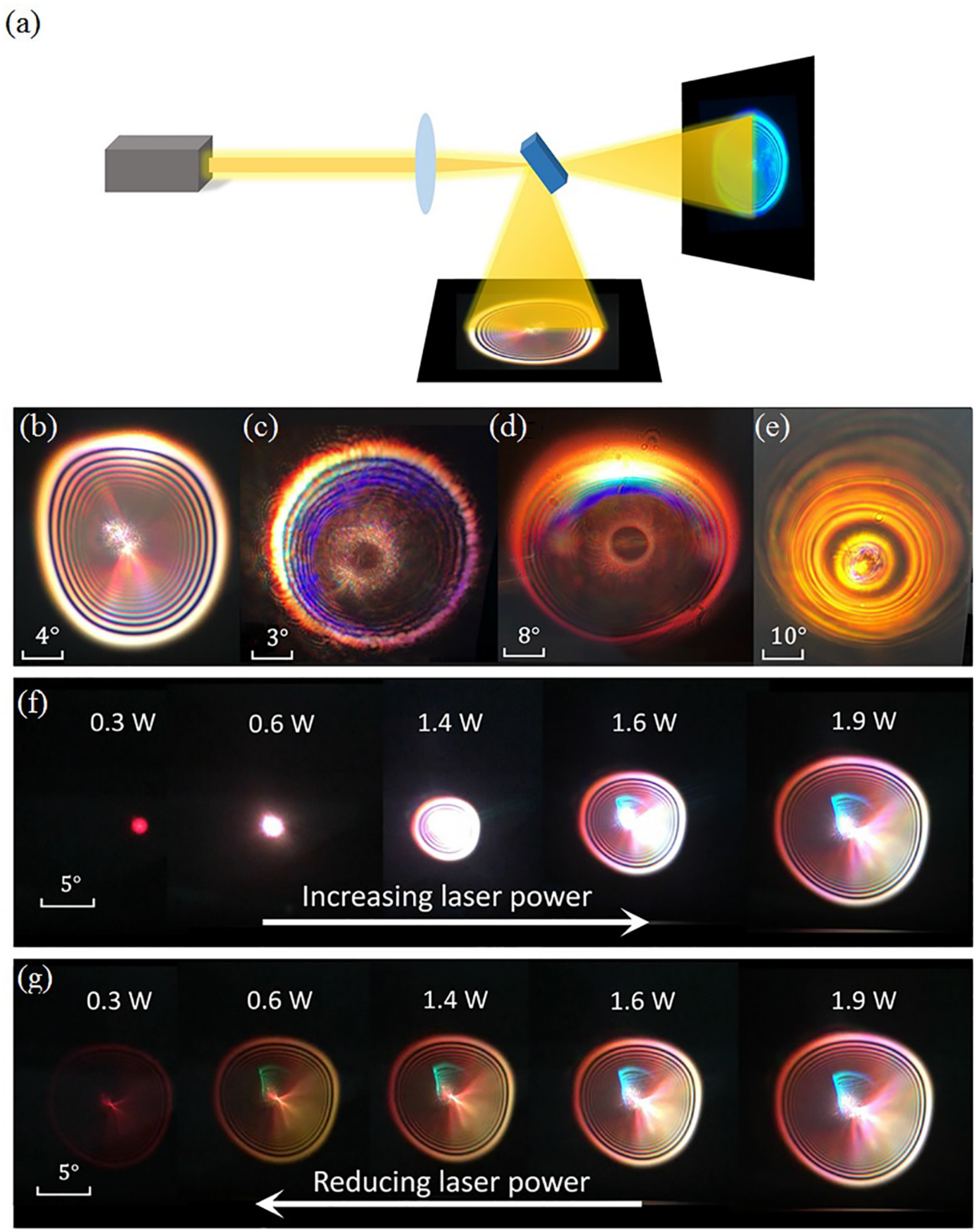

Fig. 1. Focus white-light laser into solids, many colorful rings come out. (a) Schematics of the experimental setup. A pulsed white laser is focused into a solid material, coherent rainbows can be observed in reflection mode and/or transmission mode. (b) Coherent rainbows from colored glass (in reflection mode). The bar indicates the scale of the outgoing angle. (c) Coherent rainbows (in transmission mode) from plastics, wax (d), and ice (e). (f) Increase the laser power into the colored glass from zero to maximum power (1.9 W) smoothly in about 30 s, coherent rainbows start to appear. (g) Reduce the laser power smoothly from maximum to zero in about 20 s, the coherent rainbows shrink at first. Afterwards, the interference pattern stays unchanged except becoming darker and darker.

In summary, we observe coherent rainbows in many solids with a white laser. We find out that the laser-induced optical-path difference leads to interference of light, resulting in the coherent rainbows.

Conflict of interest

The authors declare that they have no conflict of interest.

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