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Enhanced light diffraction from a double-layer microsphere lattice

Hideki T. Miyazaki[a)]
National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan and PRESTO, Japan Science and Technology Corporation, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan

Hiroshi Miyazaki
Department of Applied Physics, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Norio Shinya
National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

Kenjiro Miyano
Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan

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Anomalously strong diffraction, whose efficiency is as high as 55%, has been observed from a double-layer microsphere lattice. The enhancement is due to the specular resonance scattering from two spheres in contact, each belonging to the top and bottom layers of the double-layer, respectively. The system thus works as a single layer two-dimensional (2D) lattice of bispheres. No enhancement is observed from a single-layer lattice nor from triple-layer lattice. It functions as a "blazed" transmission grating with 2D spectral dispersion compared with the one-dimensional dispersion in ordinary linear gratings. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1623932]

Numerous efforts have been made in search for a system that realizes photonic crystals since the proposal of the concept.[1] A lattice of dielectric microspheres is a promising candidate. Fabrication techniques of high quality crystals[2] and optical properties such as transmission,[3] propagation,[4] or emission[5] have been extensively studied. However, little has been investigated on diffraction properties of microsphere crystals.[6] In this letter, we show that a double-layer lattice of micrometer-sized dielectric spheres exhibits anomalously strong diffraction, which is hardly observed for lattices with other numbers of layers, and that the efficiency is comparable to that of conventional blazed diffraction elements.

Close-packed L-layer lattices ($L=1,2,3$) were assembled on a glass substrate using polyviniyltoluene spheres (refractive index $n=1.58$) with a diameter of $D=2.10\ \mu$m by piezoelectric micromanipulator installed in a scanning electron microscope.[7] The substrate was coated with a 190-nm-thick indium tin oxide layer for conductivity and with an 80-nm-thick polystyrene layer for adequate adhesion to the spheres. The spheres were not coated with conductive materials. They were manipulated with a gold-coated glass needle. Figure 1 presents lattices of $L=2$ and 3. Although the lateral extent of the lattices is limited, the lattices showed sharp diffraction patterns; the system is judged to be sufficiently large for our purpose.

The lattices were illuminated from the substrate side with a collimated beam of He–Ne laser (wavelength $\lambda=0.633\ \mu$m, size parameter of the sphere $S=\pi D/\lambda=10.4$) at various incidence angles θ [Fig. 2(a)]. The lattices consist of stacks of triangular lattice layers, which have two major directions Γ–M and Γ–K. In this letter, results for the oblique incidence in the Γ–M direction are discussed. The diffracted light was collected with an objective lens with a numerical aperture of 0.95. At its back focal plane, the Fourier image of the lattice is formed. This corresponds to the $k_z=0$ plane in the wave vector space, and was magnified and projected onto a cooled charge-coupled-device (CCD) camera. Since an aperture slightly larger than the lattice was placed on the image plane of the objective lens, only the scattered light from the lattice reached the CCD. The incident light was linearly polarized, and no analyzer was used. The transmission spot is located at $\mathbf{k}_{i\parallel}=(k\sin\theta,0)$ on the CCD image, where $k=2\pi/\lambda$. In Figs. 2(b)–2(h), the CCD images are presented in such a manner that the transmission spot is always located at the center of the figures.

Figure 2 shows a series of Fourier images of a double-layer crystal obtained as θ was decreased from 30° to $-58°$ for p-polarized incidence. A pair of spots at the upper and lower edges at $\theta>0°$ are taken over by another spot at the left edge at $\theta\simeq 0°$. The spot moves rightward along the k_x axis as θ decreases, and it passes by the transmission spot at the center at $\theta\simeq -35°$. No significant polarization dependence was seen. The results for $L=3$ were similar, but the intensity of all spots were smaller than that for $L=2$.

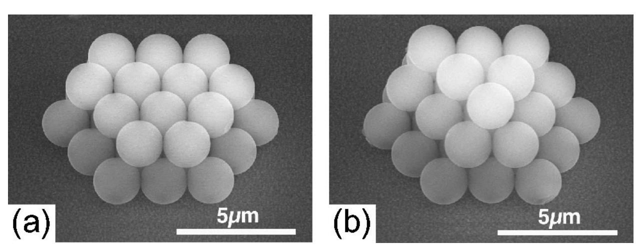

FIG. 1. Scanning electron micrographs of the lattices of (a) $L=2$ and (b) $L=3$, consisting of 31 and 37 spheres, respectively; the latter has a face-centered-cubic structure. Another lattice of $L=1$ made of 19 spheres was also assembled.

[a)]Electronic mail: miyazaki.hideki@nims.go.jp

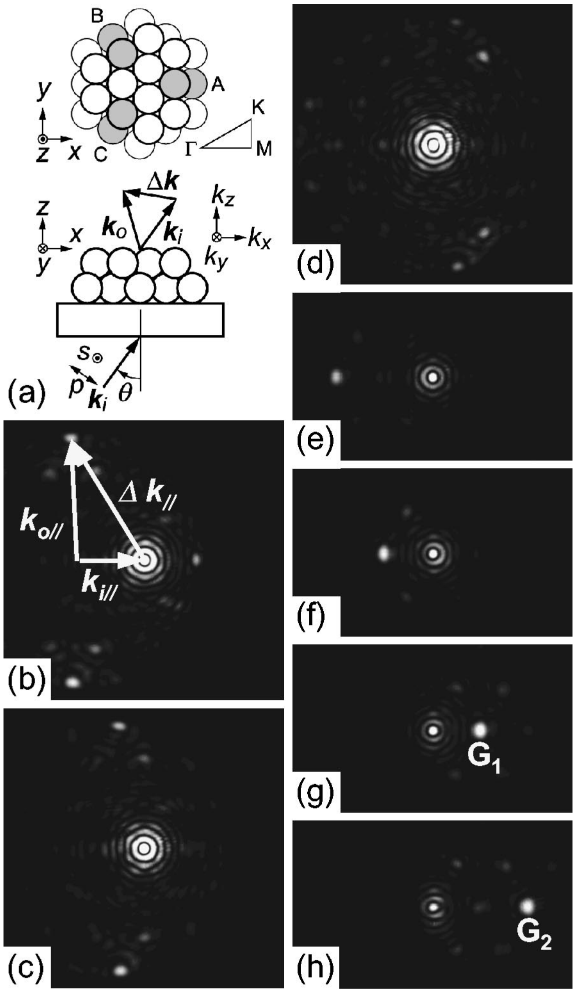

FIG. 2. (a) Coordinate system. The substrate surface coincides with the xy plane, and the Γ–M direction of the lattice is parallel to the x axis. The wave vector of the incident light $\mathbf{k}_i$ lies in the xz plane and makes an angle θ with the z axis. The polarization perpendicular and parallel to the incidence plane are defined as s and p, respectively. $\mathbf{k}_i$ receives a momentum transfer $\Delta\mathbf{k}$ by diffraction, and goes out as $\mathbf{k}_o$. Their xy components are denoted as $\mathbf{k}_{i\parallel}$, $\Delta\mathbf{k}_{\parallel}$, and $\mathbf{k}_{o\parallel}$, respectively. (b)–(h) Wave vector image of the double-layer lattice for representative θ values. (b) $\theta=30°$, (c) 18°, (d) 4°, (e) $-10°$, (f) $-22°$, (g) $-46°$, and (h) $-58°$. Displayed areas are $20\times 20\ \mu\mathrm{m}^{-1}$ for (b)–(d) and $20\times 12\ \mu\mathrm{m}^{-1}$ for (e)–(h), and the intensity is plotted in a linear scale. Intensity in (b)–(d) is enhanced by a factor of 4.

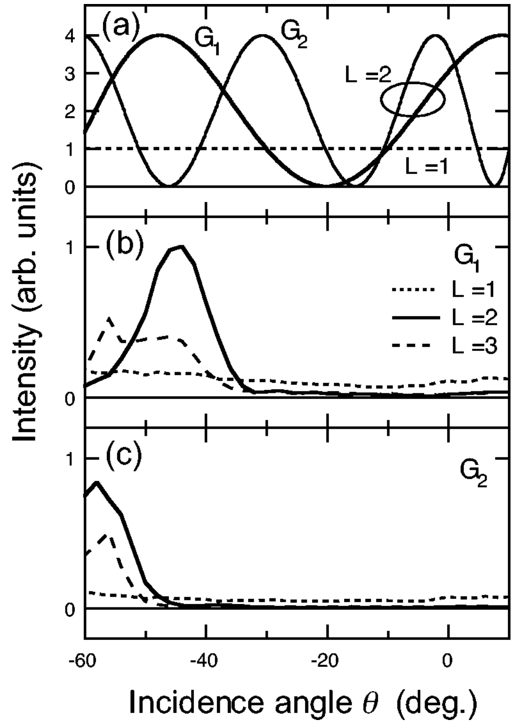

FIG. 3. θ dependence of the diffraction intensity for G_1 and G_2. (a) The results of calculation for lattices of $L=1$ and 2 based on the interlayer-interference model. (b), (c) The results of the experiment for p polarization for G_1 and G_2, respectively.

The appearance of a diffraction spot at a certain θ value as shown in Fig. 2 is a characteristic of Bragg diffraction from a three-dimensional lattice; for a two-dimensional (2D) lattice, all diffraction spots (rods) should have finite fixed intensity in the $k_z=0$ plane all the time. Considering the shape of our crystals, we found it convenient to analyze the result in terms of the interference of diffraction from individual monolayer sheet (called interlayer-interference model, hereafter). Let us consider the diffraction from a L-layer stack of infinite 2D periodic lattice of small homogeneous scatterers.[8] The reciprocal lattice vectors of the 2D lattice can be expressed as $\mathbf{b}_1=(4\pi/\sqrt{3}D,0,0)$ and $\mathbf{b}_2=(-2\pi/\sqrt{3}D,2\pi/D,0)$. Diffracted wave from a 2D lattice is written as $\mathbf{k}_{o\parallel}=\mathbf{k}_{i\parallel}+v_1\mathbf{b}_1+v_2\mathbf{b}_2$, where v_1 and v_2 are integers. When L lattice planes are stacked according to a displacement vector $\mathbf{a}=(\sqrt{3}D/6,D/2,\sqrt{6}D/3)$, the phase difference of the diffracted waves from neighboring planes is obtained as $\phi=\mathbf{a}\cdot\Delta\mathbf{k}$. As a result of the interference of the diffracted waves from L planes, the total diffraction intensity is modified by a factor $\sin^2(L\phi/2)/\sin^2(\phi/2)$.

The intensity corresponding to the diffraction spots for G_1 and G_2 in Figs. 2(g) and 2(h), respectively, is calculated using the interlayer-interference model and is shown in Fig. 3(a). The intensity for $L=1$ is independent of θ as mentioned earlier. For $L=2$, the intensity varies sinusoidally as a function of θ. The peak intensity is four times as large as that for $L=1$. For $L=3$, the peak intensity becomes nine times as large and the peak width becomes narrower.

The experimental results of the diffraction intensity curves for G_1 and G_2 are shown in Figs. 3(b) and 3(c). The peak positions at $\theta\simeq-45°$ for G_1 and $\theta\simeq-60°$ for G_2 seem to be similar to the results of the calculation. However, there are two essential differences between the experiment and the calculation. First, the experimental intensity curve does not oscillate as a function of θ but has only one peak. Second, the peak intensity in the experiment does not monotonously increase in proportion to L^2, but shows more complicated behavior; the peak intensity increases by a factor of 5.3–8.3 for $L=2$, then decreases to a half for $L=3$. Furthermore, it was found that the diffracted waves from the triple-layer lattice mainly arise from the two-layered region at the edge; this was confirmed by changing the shape and the size of the aperture placed on the image plane of the objective lens in various ways.[9] The discrepancy between the experiment and the calculation is serious, even though the simplification in the model is considered. A superposition principle does not apply and we should seek a diffraction mechanism specific to the double-layer lattice.

Rather than as a stack of two single-layer lattices, a double-layer lattice should be viewed as a 2D lattice of bi-spheres, assembly of two identical dielectric spheres in con-

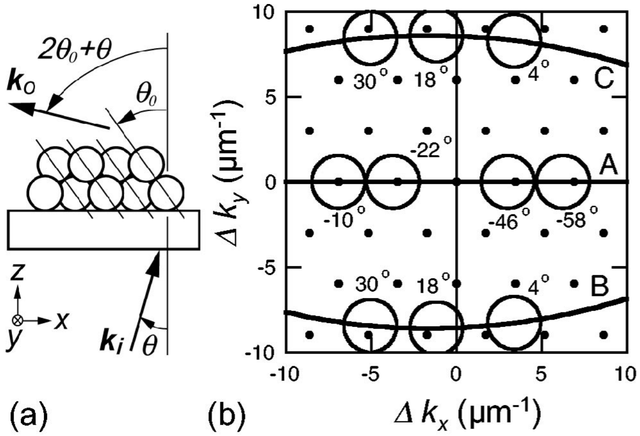

FIG. 4. (a) Specular reflection of the incident light by bisphere As. $\theta_0 = 35.3°$. (b) Transition of the position of the specular resonance spot (circles) in the wave vector space. Dots represent the reciprocal lattice points of the 2D lattice. The diameter of the circle corresponds to the angular width (full width at half maximum) of the specular resonance waves.

tact. Bispheres in the range of $S \gtrsim 5$ and $n = 1.2 - 2.2$ produce strong specular reflection for an arbitrarily polarized light incident within an angle of 40° to the symmetry axis.[10,11] This phenomenon is called specular resonance. The results observed in this letter is understandable as the diffraction from a 2D array of specular resonance sources. As shown in Fig. 2(a), the double-layer lattice can be decomposed into three types of bispheres A, B, and C. For example, bisphere As specularly reflect the incident light in the *xz* plane as depicted in Fig. 4(a). Only when the direction of this reflection matches with that of a diffracted wave from the 2D lattice, significant diffraction arises. Figure 4(b) illustrates the positions of the specular resonance spots by bispheres A, B, and C for the representative θ values in Fig. 2. All of the diffraction spots observed in Fig. 2 are successfully explained by the coincidence between the reciprocal lattice points and the specular resonance spot. This model is also applicable to the diffraction in the Γ–K direction.[9] Because the intensity of the Bragg peaks for a double-layer crystal is not determined by the interference of two waves, enhancement over the factor of 4 is not surprising. Since the specular resonance is peculiar to bispheres,[9] a triple-layer lattice, a 2D lattice of trispheres, does not show any enhancement.

Since the diffraction from the double-layer lattice originates from twelve bisphere units in our experiment, the intrinsic diffraction efficiency of the double-layer lattice can be obtained as the ratio of the diffraction intensity to the intensity incident on the twelve spheres of the first layer. The maximum efficiency was estimated to be 55% for *p* and 52% for *s* polarization (spot G_1). These values are comparable to the typical efficiency (50%–80%) of the conventional blazed transmission gratings,[12] although the lattice used here is not optimized at all as a diffraction device. The small polarization dependence also suggests its promising nature as a grating.

In summary, double-layer structures of 2D periodic lattices can work as efficient blazed diffraction devices, in which a unit made of adjacent elements in the first and the second layer behaves as a micro-optical system component. A double-layer lattice of microspheres with a large domain size has been realized by self-assembly technique.[13] It would be useful as a low-cost blazed transmission grating, if point defects are sufficiently reduced. Optimum diameter and refractive index of spheres for a grating should be determined by rigorous calculation.[14,15] Since each sphere in the bisphere is working as a focusing and a collimating lens,[11] this concept is applicable to an efficient and tunable microelectromechanical diffraction systems comprised of two optimized microlens arrays. It is of great interest to search for a phenomenon caused by repeated specular resonance in much thicker microsphere crystals.

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