Periodic waveguide structures exhibit many interesting optical properties and can be used for spontaneous-emission inhabitation, photonic bandgaps, optical filtering, and distributed-feedback and distributed Bragg reflector lasers. Most of the structures that have been designed are one dimensional (1D) coupling beams propagating in opposite directions. Two-dimensional (2D) periodic waveguide structures can lead to several unique schemes for controlling and manipulating light waves. For example, microcavities were fabricated by use of waveguide-integrated photonic crystals. Since the most commonly used fabrication technique for periodic structures at optical wavelengths is lithography, researchers have focused on 2D structures consisting mainly of air columns in a substrate. Although lithography is a mature technique for microelectronics applications, it presents difficulty for fabrication of structures on a nanometer scale.

In this Letter we demonstrate, for what is to our knowledge the first time, two-dimensional (2D) corrugated waveguides at optical wavelengths obtained by use of 2D colloidal crystals. Self-assembly of colloid particles occurs on the surface of a planar waveguide. These colloidal crystals, which act as 2D gratings on the waveguide, make the system a 2D corrugated waveguide. To prove that these particles are actually a part of a waveguide structure we performed experimental studies of light coupling into and out of the waveguide structure. The diffracted light shows interesting optical properties that exist only in such 2D grating structures. Field distribution of the fundamental mode in the structure is studied into and out of the waveguide structure. The diffracted light shows interesting optical properties that exist only in such 2D grating structures. Field distribution of the fundamental mode in the structure is studied.

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In this Letter we demonstrate, for what is to our knowledge the first time, two-dimensional (2D) corrugated waveguides at optical wavelengths obtained by use of 2D colloidal crystals. Self-assembly of colloid particles occurs on the surface of a planar waveguide. These colloidal crystals, which act as 2D gratings on the waveguide, make the system a 2D corrugated waveguide. To prove that these particles are actually a part of a waveguide structure we performed experimental studies of light coupling into and out of the waveguide structure. The diffracted light shows interesting optical properties that exist only in such 2D grating structures. We believe that the 2D corrugated waveguide structure can lead to new schemes for optical filters, light couplers, 2D optical processors, and microcavities. In addition, since the grating period is determined by the size of the colloidal particles, this method of grating fabrication will be useful for making periodic structures for short-wavelength applications.

Figure 1 shows the 2D corrugated waveguide structure and the experimental setup for studying light coupling out from the structure. The waveguide (Photonic Integration Research, Inc., Columbus, Ohio) was a Ge:SiO$_2$ guiding layer that was 6 $\mu$m thick and had a refractive index of 1.467. Below that layer was a SiO$_2$ buffer layer that was 20 $\mu$m thick and had a refractive index of 1.457. The substrate was Si. A single layer of 2D colloidal crystal was deposited upon the surface of the structure by convective assembly. The colloids were a monodispersed latex suspension (Bangs Laboratories, Fishers, Ind.) with particles that were 980 nm in diameter and had a refractive index of 1.59 and a concentration diluted to 0.1%. It has been shown that colloidal crystals formed directly upon solid surfaces are usually polycrystalline. Figure 2(a) shows the far-field diffraction pattern of laser light (633-nm wavelength) on these polycrystalline crystals formed upon a glass substrate. When we used a focused beam (<15- $\mu$m spot size), the sample showed a diffraction pattern of single crystals [Fig. 2(b)]. The diffraction angle was 45°, corresponding to the period of the grating, which was a few percent larger than the ideal value, $\sqrt{3}/2d$, where $d$ is the diameter of the latex particle. Both the far-field diffraction pattern and atomic-force microscope pictures show that the crystals are arrays of 2D hexagonal closest-packed particles.

Our experimental study of colloidal crystal-assisted light coupling into and out of the waveguide was carried out with a He–Ne laser as the light source. As shown in Fig. 1, incident light was coupled into the main mode of the waveguide by a prism coupler placed upon the surface of the planar waveguide. When the guided beam reached the colloidal grating area, we observed that the output light formed an arc on the screen, as shown in Fig. 3(a). The picture was taken from a white screen by use of a regular camera.

![Fig. 1. Experimental setup of the 2D corrugated waveguide with colloidal crystals. Inset: vector diagram for phase matching.](image-url)
This arc is the result of the phase-match requirement, where the output propagation vector $K_{\text{out}}$ intersects the grating vector $K_g$ in space, as shown in Fig. 3(b). In fact, assuming that the waveguide beam is propagating along the $x$ direction, it can be found that the components of $K_{\text{out}}$ obey the following phase-matching conditions:

$$K_{\text{out},x} = K_w + K_g \cos \phi,$$
$$K_{\text{out},y} = K_w + K_g \sin \phi,$$
$$K_{\text{out},z} = -[(2\pi/\lambda)^2 - K_{\text{out},x}^2 - K_{\text{out},y}^2]^{1/2}.$$

Here $K_w = (2\pi/\lambda)n^*$ is the waveguide vector, $n^*$ is the waveguide mode index, and $\phi$ is the angle between $K_g$ and the $x$ axis. For polycrystalline colloidal crystals with perfectly packed hexagons, $K_g = 2\pi(\sqrt{3}/2d)^{-1}$. Using a model for the index profile of the structure that assumes index averaging along constant $z$ planes, as shown in Fig. 4, we found that the TE$_0$ mode index $n^*$ is 1.466. Therefore the maximum value of $\phi$ for the parameters used in our experiments is $142^\circ$. This value corresponds to a maximum output angle $\psi = 28^\circ$, which is consistent with our experimental measurement. Mode-profile calculation shows that only approximately $1.6 \times 10^{-4}$ of the mode power is localized in the layer formed by the particles. Note that the structure that was used in this study is not optimized at all. Nevertheless, this shows that the particles and the waveguide are optically coupled. It can also be shown that the mode power in the colloidal layer can be increased if a waveguide structure with stronger index step and smaller thickness of the guiding layer is used. We also performed experiments in which light was coupled into the waveguide by these gratings. When the input light was incident upon the grating area at the proper incident angles, we observed light emerging from the edge of the waveguide. These experimental results show that the structure can be used as a simple optical coupler.

It is interesting to know the mode profile in this structure to understand better the physics and to improve the design of the structure. In particular, since the latex particles have higher refractive indices than those of the neighboring layers, there is a possibility that a guiding layer is formed by these particles. Treating the grating layer as a layer with an index profile that is uniform along the $y$ direction and varying along the $z$ direction, according to the curve shown in Fig. 4, we calculated the field profile of the modes. When the fundamental mode is the only mode excited by the light coupled through the prism, as in the case of our experiments, the field profile in the 2D corrugated waveguide region shows weak coupling between the grating and the waveguide. We also found that the layer of particles on top of the Ge:SiO$_2$–SiO$_2$ structure does not maintain its own guide mode. However, it would have a mode for a substrate with a refractive index $n < 1.45$. 

![Fig. 2](image1.png) Far-field diffraction pattern of (a) polycrystalline and (b) single colloidal crystals upon a glass substrate.

![Fig. 3](image2.png) (a) Intensity pattern of output light from a 2D corrugated waveguide with colloidal crystals and (b) phase-matching conditions for the pattern in space.

![Fig. 4](image3.png) Index and mode profiles of the field in the 2D corrugated waveguide.
Although our experiments have shown only light coupling into and out of the waveguide structure by the colloidal gratings, it is obvious that this type of structure can be used for many other devices similar to those based on 1D waveguide gratings, such as narrow-band filters and distributed-feedback mirrors. 2D distributed Bragg reflectors and microcavities can also be realized if one or more particles in the crystal array are removed. Most of these applications require single colloidal crystals on a waveguide. Although making large single colloidal crystals is still an active research field, a few approaches have been tested. One way is to use an intermediate layer of fluid between the colloid particles and the substrate. By proper control of the evaporation rate of the colloids and the fluid, single crystals as large as 1 mm can be produced; this is large enough for most optical device applications. It should be noted that for practical device applications these colloidal gratings should be solidified. This can be done with recently developed techniques that use colloidal crystals as a template.

Our technique for waveguide grating fabrication has several advantages over traditional optical lithography and electron-beam–ion-beam lithography. Holographic lithography can normally produce a 1D grating and is not suitable for creating precise 2D patterns. Optical projection lithography presents difficulty for making 2D gratings with periods smaller than 1 μm. Electron-beam or ion-beam lithography can produce 1D or 2D gratings with 100-nm periods. However, these methods require expensive facilities and well-trained personnel to do the work in a cleanroom environment. The technique described above can potentially provide a simple low-cost method for making high-quality 2D gratings with good uniformity and small periods.

In summary, we have demonstrated 2D corrugated waveguides at optical wavelengths by use of 2D colloidal crystals. We performed experimental studies of light coupling into and out of the waveguide structure. The observed diffracted light coupled out from the 2D structures forms an arc in space. Our analysis showed that coupling between the gratings and the waveguide depends on the difference in the refractive indices of the materials used. Although our structure is not optimized, we believe that our results may lead to new schemes for optical filters, light couplers, 2D optical processors, and microcavities as well as to a practical technique for making periodic structures for short-wavelength applications.

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