Optical coupling between monocrystalline colloidal crystals and a planar waveguide

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We have experimentally demonstrated an optical material structure consisting of monocrystalline colloidal crystals and a planar waveguide. We have performed experimental studies of light coupling into the waveguide structure via colloidal gratings, as well as the multiplexing capability of the structure. Effective index obtained from measured parameters agrees well with theoretical calculations. Effect of crystal nonuniformity on diffraction line shape and width, as well as possible applications are discussed. © 1999 American Institute of Physics.

Photonic crystals are one type of interesting optical material structures under development.1,2 Recently, there is an intensive effort to study self-assembly of colloidal particles with a motivation to fabricate photonic crystals with lattice spacings of the order of optical wavelengths. This started with self-assembly colloidal suspensions to form three-dimensional photonic crystals.3,4 Later, macroporous dielectric materials with high contrast in refractive index were fabricated using latex crystals as templates.5–7 Recently, we have demonstrated a two-dimensional (2D) periodic structure consisting of a planar waveguide and polycrystalline colloidal crystals.8 In this letter, we report optical coupling between monocrystalline colloidal crystals and a planar waveguide. This structure has many interesting optical properties, and may lead to two-dimensional photonic circuits and microcavities.9 In addition, we also demonstrated the possibility of the use of the structure as optical filters, optical couplers, and wavelength demultiplexers.

Highly ordered 2D arrays of latex particles can be obtained via convective assembly.11 Once the assembly of colloidal particles is formed on the surface of a planar waveguide, the colloidal crystal, acting as 2D gratings on the waveguide, make the system a 2D corrugated waveguide. In our experiments, a waveguide (supplied by Photonic Integration Research Inc., Columbus, OH) has a Ge:SIO2 guiding layer of 6 μm in thickness and refractive index of 1.467. Below that is a SiO2 buffer layer of 20 μm in thickness and refractive index of 1.457. The substrate is Si. A single layer of 2D colloidal crystal was deposited on the surface of the structure using convective assembly.11 The colloidal was monodispersed latex suspension (Interfacial Dynamic Corp.) with particles of 495±10 nm in diameter, refractive index of 1.59, and concentration diluted to 1%. Pictures from atomic force and optical microscopes show that hexagonal gratings, which are a highly ordered layer of latex particles, formed on the waveguide surface. The period of the grating (A) is found to be 422 nm, which is equal to 3/2d, where d is the diameter of the latex particle.

To study the optical property of this waveguide structure, we have performed experiments of light coupling between the 2D gratings and the waveguide. In the experiments [Fig. 1(a)], an incident light was focused by a lens (f =12.5 cm) into a spot of around 150 μm on the gratings. With a proper incident angle (θ), input light can be coupled into the waveguide through the interaction between the optical modes at the interface of gratings and the waveguide. The excited wave in the waveguide obeys the phase-matching condition, which can be described by the following equation:

\[ \mathbf{K}_i + \mathbf{K}_g = \mathbf{K}_w. \] (1)

Here \( \mathbf{K}_i \), with magnitude of (2π/λ)\sin(θ) and assumed to be in x direction, is the component of the incident wave vector in the waveguide, \( \mathbf{K}_g \) is the grating vector with magnitude of 2π/Λ, and \( \mathbf{K}_w \) is the waveguide vector with magnitude of (2π/λ)n*, where n* is the waveguide mode index. This relationship can also be illustrated in the diagram in Fig. 1(b). It can be seen that the direction of the wave propagating in the waveguide depends on directions and magnitudes of \( \mathbf{K}_i \) and \( \mathbf{K}_g \). Since the magnitude of \( \mathbf{K}_i \) can be...
changed by varying the incident beam angle, it is possible to control the propagation direction of wave $[\phi_1$ or $\phi_2$ in Fig. 1(b)] in the waveguide by using different incident angles. When an incident beam has multiple wavelengths, different wavelengths will travel in different directions according to Eq. (1). These propagation direction control and wavelength demultiplexing capabilities are unique properties in this type of 2D waveguide grating structures.

We have experimentally demonstrated the coupling of an incident light (wavelength $= 633$ nm) into two directions (up beam $K_w_1$ and down beam $K_w_2$) in the waveguide by changing the incident angle, as shown in Fig. 2. It can be seen that as we change the incident angle from $-2.25^\circ$ to $-3^\circ$, more light power is coupled into the up beam. From the locations of these two peaks and assuming perfect hexagonal structure of the grating, we can also estimate the effective index of the waveguide by using Eq. (1). Using the measured results, we have estimated $n^*$ to be 1.462. This value agrees well with our theoretical calculation based on a simplified waveguide model. In the model, we treated the layer of particles as a layer with the index profile uniform along $xy$ plane, but varying along $z$ direction according to the curve shown in Fig. 3. The index at given $z$ was calculated by averaging the index values of structure in $xy$ plane. The effective indices $n^*$ for three existing TE modes are found to be 1.466, 1.464, and 1.460. The TE mode profiles are also presented in Fig. 3. It is shown that higher order modes have higher percentage of optical power localized in the particle layer. This indicates that there is a stronger coupling between the input and the higher order modes, and the measured effective index is closer to those of the higher order modes. Similar relations between effective index and modal profiles have been found for TM modes. In the experiments, we were not able to separate these waveguide modes due to the limited size of the single crystal.

The width and the shape of the peaks in Fig. 2 are affected by the parameters of the waveguide and the gratings. The shape of the peaks appears to be Lorentzian, and the widths are found to be $2.70^\circ$ and $1.37^\circ$ for the up and down beams, respectively. It is well known that nonuniformity of gratings is the main factor for line broadening. In our study, we found from pictures obtained using atomic force micro-

![FIG. 2. Output power of light output from the waveguide vs incident angle.](image1)

scope that there are small distortions in certain grating areas. Most of these distortions are caused by the variations in particle diameter, resulting in nonstraight grating lines. These distortions introduce errors in the phase of the periodic grating and lead to Lorentzian broadening. The diffraction line-width depends on the amount of distortions along the diffracting grating vector directions. Obviously, there are a larger amount of distortions along the grating vector for up beam diffraction than that for down beam.

Although our experiments have only showed optical coupling between a planar waveguide and colloidal gratings, it is obvious that this type of structures can be used for many other devices similar to those based on 1D waveguide gratings, such as narrow-band filters, and distributed feedback mirrors. This structure could also provide an important step towards the creation of photonic wiring at optical wavelengths. This type of wiring was demonstrated at microwave wavelength by using two-dimensional arrays of alumina rods. We can realize such a structure at optical wavelengths by removing a few rows of latex particle in the 2D corrugated waveguide. Microcavities may also be realized if certain portion of the particles are removed. Most of these applications require high quality single colloidal crystals on a waveguide. While making high quality 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. It should be noted that, for practical device applications, these colloidal grating should be solidified. This can be done utilizing recently developed techniques using colloidal crystals as a template.

In summary, we demonstrated two-dimensional corrugated waveguides, and shown that they can be used for optical coupling and wavelength demultiplexing. These structures can be used for many other devices similar to those based on 1D waveguide gratings, such as narrow-band filters, and distributed feedback mirrors. This structure could also provide an important step towards the creation of photonic wiring at optical wavelengths. This type of wiring was demonstrated at microwave wavelength by using two-dimensional arrays of alumina rods. We can realize such a structure at optical wavelengths by removing a few rows of latex particle in the 2D corrugated waveguide. Microcavities may also be realized if certain portion of the particles are removed. Most of these applications require high quality single colloidal crystals on a waveguide. While making high quality 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. It should be noted that, for practical device applications, these colloidal grating should be solidified. This can be done utilizing recently developed techniques using colloidal crystals as a template.
gated waveguides at optical wavelength by using two-dimensional colloidal crystals. We performed experimental studies of light coupling into the waveguide structure via 2D gratings, as well as the multiplexing capability of the structure. Effective index obtained from measured parameters agrees well with that obtained from theoretical calculations. We believe that our results reported here may lead to schemes for optical filters, light couplers, 2D optical processors, new photonic wiring, and microcavities.

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