Industrial application of three-dimensional colloidal photonic crystals made in space

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Abstract. Three-dimensional colloidal photonic crystal can be utilized as optical pulse control devices for ultra-short laser pulses as short as a few tens of femtosecond. Using a recently developed colloidal crystallization method, a few centimetre sized single colloidal crystals were made. By shining femtosecond laser pulses onto one hundred micrometer thick colloidal crystal, we confirmed a pulse shape change clearly. Under a collaborative project within Japan Aerospace Exploration Agency, we have grown such colloidal photonic crystals at the international space station, successfully. Optical and mechanical properties of the colloidal photonic crystal will be discussed in more detail to figure out their industrial high power laser application.

1. Introduction

Photonic crystal [1,2] is one of a new device/material to realize wide variety of optical application from low power semiconductor lasers to high-energy laser fusion. There are different kinds and dimension of photonic crystals discussed in previously reported articles. We are currently investigating colloidal photonic crystal [3] structures that can be grown to a large single three-

Figure 1. Scanning electron microscope image of silica spheres with their sizes around 120nm.

Figure 2. Charge separated colloidal spheres arranged in three-dimensional manner by self-organization in transparent pure water.
dimensional crystal structures, under a wide range of collaboration work among universities, governmental research centres, industries and friendly works with the Russian space agency ROSS COSMOS and ENERGIA. The colloid crystal requires a few hundred nanometer transparent same-sized spheres arranged three-dimensionally in a few hundreds nanometer separation with a few nanometer accuracy. Without having same-sized spheres (see figure 1 as an example of such well-size-controlled spheres), even a few tens of micrometer size of single crystal could not be realized. Using chemical method and particle separation, such size-controlled spheres were obtained. Figure 2 shows a schematic diagram of a three-dimensional colloidal photonic crystal with transparent spheres dispersed in pure water. Due to charges attached on the spheres, there exists Coulomb repulsion (or attractive forces arising from many body effect) among them and re-arrange their positions. As the result of their interaction in a container with a suitable sphere concentration, one can realize well-organized and optically matched colloidal crystal structure. By fixing their positions using UV resin dissolved in the water, we can obtain a soft photonic crystal with the size of the container.

Photonic crystals show large group dispersions [4] that vary pulse duration and transit time of ultrashort laser pulses at their band edges. Current high-power femtosecond lasers adopt “chirp amplification” technique [5] which first stretch femtosecond pulses, amplify the stretched pulses, and then compress the pulses into the original pulse duration using positive and negative dispersion optical grating devices. For a very high-power femtosecond laser like a peta watt peak-power laser, highly dispersive and high damage threshold materials or optical configurations are required to change pulse shapes. Photonic crystals having a band edge at around 800nm are the candidate for such ultra-short high power Ti:Sapphire laser with less than a few tens of femtosecond pulse duration.

In this paper, we will discuss how photonic crystals act as such pulse control devices for industrial usage and some part of our recent activities to realize large crystals using the international space station floating 400km above our heads.

2. Optical properties of soft colloidal photonic crystals

Optical properties of such photonic crystals are determined by their composing materials and their arrangements, simultaneously. For instance, a photonic crystal made with silica spheres having refractive index around 1.5 or with TiO$_2$ spheres having their refractive index about 2.2, dispersed in water, shows completely different optical band structure as depicted in Figure 3. The sphere diameters are assumed to be the same and the spheres were arranged in a one-dimensional manner. The horizontal axis corresponds to normalized wavelength for the optical band (so-called photonic band or stop band) and the vertical axis corresponds to theoretical transmission for 31 array of spheres arranged one-dimensionally. As clearly seen in the figure, the higher the refractive index of the spheres, the wider and deeper the photonic band. We select various transparent spheres for different application purposes. Silica may be good for narrow band application while TiO$_2$ is good for high reflection application with thinner size. Polystyrene spheres are good for lower cost devices.

![Figure 3. Theoretical transmission curves of various photonic crystals using different sphere materials in water, with 31 arrays of arrangements.](image-url)
2.1. Angle dependent spectral transparency

Toyotama, Sawada and Kanai [6] fabricated a 100 micrometer thick photonic crystals using polystyrene spheres enclosed in quartz containers. Their angular spectral characteristics were measured with spectrometer in visible range as shown in figure 4. The photonic crystal sample was set perpendicular to the spectrometer optical axis first and then rotated against the axis. The photonic band wavelength at a long wavelength shifts from 860nm toward 750nm while another band at shorter wavelength shifts from 580nm to 670nm (indicated by the arrows). The band shifts as function of the rotation angle are summarized in figure 5. Each photonic band was assigned to a band along either (111) or (002) plane by Sawada, respectively.

![Figure 4](image1.png)  
**Figure 4.** Angular spectral transmission characteristics of a 100 micrometer thick photonic crystal with polystyrene spheres.  

![Figure 5](image2.png)  
**Figure 5.** Photonic band shifts as function of the rotation angle of the 100 micrometers thick photonic crystal.  

2.2. Photonic band tunability by mechanical compression of soft photonic crystal

As mentioned previously, our three-dimensional photonic crystal is soft due to lower concentration of UV resin to fix the three-dimensional sphere arrangement. By compressing the photonic crystal, one can easily tune the photonic band energy continuously. Iwayama[7] made a single soft photonic crystal and tested the optical tunability using spectrometer in visible range. Figure 6 shows the tunability data as function of the crystal compression ratio $t/t_0$ where $t_0$ represent original thickness of the crystal and $t$ as the compressed thickness. The vertical axis corresponds to the lowest transmission wavelength within the photonic band under the test. The photonic band shifts toward shorter

![Figure 6](image3.png)  
**Figure 6.** Wavelength shifts arising from the mechanical compression of a soft photonic crystal. As the thickness of the crystal becomes thinner, the photonic band shifts toward shorter wavelength linearly from 630nm to 500nm in this case with about 20% of thickness compression.
wavelength as the crystal is compressed. It is due to the separation between the spheres being reduced and changing their photonic band structure. This tunable nature of the soft photonic crystal is feasible for some industrial application such as spectroscopy or wavelength filtering.

3. Pulse profile control with photonic crystals

As Imhoff [4] demonstrated earlier, a colloidal crystal can vary pulse shape and pulse propagation time in the structure more effective than normal transparent material like a glass at their band edges. By using a large bulk photonic crystal, one may realize large dispersion control for ultra-short pulses with high peak power in a range of tera watt to peta watt. However, there was no technology to grow a three-dimensional photonic crystal as large as a 1cm cube. Therefore, we, under collaboration among universities, governmental research centers, and industries, worked together to realize such large size single crystals. Such crystal growing technique is discussed in detail in other articles by our collaborators. One may refer such articles to find out how the crystals were made[8,9].

Using the large dispersion properties at the band edge of photonic crystal, one may construct “chirp amplifier” for high peak power ultra-short pulse lasers. Figure 7 depicts an example of such chirp amplifier using photonic crystals. It was tough to amplify ultra-short pulses with a simple optical amplification configuration. Mourou adopted “chirp amplification method” to the laser amplifier. First, ultra-short seed pulse enters into a photonic crystal and the pulse duration is stretched by the dispersion of the crystal wide enough to get enough energy during its amplification. External energy is fed into the amplifier to boost up the stretched seed pulse into energetic long pulse with chirp characteristics. Then a second photonic crystal having opposite dispersion property compress the chirped and amplified pulse into original duration pulse which comes to be very high peak power laser pulse as shown. Therefore, the photonic crystals have to be strong for optical damages and show uniform dispersion in the crystals with reasonably high wavelength dispersion.

Using the 100 micrometer thick photonic crystal made by Sawada and Kanai, temporal dispersion properties were evaluated with a femtosecond Ti:Sapphire laser and a cross correlation system. The original pulse duration from the Ti:Sapphire laser was about 30fs with a peak wavelength of 805nm.

Figure 7. Example of “chirp amplifier” configuration with two photonic crystals as pulse stretcher and compressor, are shown. The triangles in this figure represent optical pulses before and after the transmission through the photonic crystals and optical amplifying material.
The photonic crystal was set within an optical beam path in the cross correlator and measured the pulse shape change as function of the crystal rotation angle to tune the photonic band wavelength against the laser spectrum. To figure out the dispersion effect arising from the photonic crystal structure, we also evaluated the pulse profiles through disordered colloid having same sphere concentration and same water thickness.

Figure 8 (a) indicates pulse duration changes as the crystal orientation changes against the incident 30 femtosecond laser pulse beam and (b) corresponds to the same angle dependence of disordered colloid sample measured by a cross correlator.

\[ T^2 = t^2 + (4 \ln 2 * \Phi'' / t)^2 \]

where \( T \) represents output pulse duration and \( t \) is for that of input pulse. The dispersion term \( \Phi'' \) is obtained from 2nd order differentiation of the wave number. For one tera watt output laser case, the amount of dispersion required is,

\[ \Phi'' = 1E5 (fs^2/mm)^2 * 42(mm) = 4.2E6(fs^2) \]

for \( t=30\text{fs} \) and \( T=393000 \text{ fs} \). One may use spheres with their refractive index around 2.1 to realize the dispersion and can make it using 40mm of single photonic crystals.

4. Optical damage threshold

We can test optical damages of photonic crystals with a Z-scan technique as illustrated in figure 9. Femtosecond laser beam is focussed with a lens and the sample passes through the optical axis of the lens. The laser intensity through the photonic crystal is measured with a photodetector. With this configuration one can determine the damage threshold and optical nonlinear effect in the photonic
crystals. As a result of Z-scan measurement for an UV resin sample adopted for the soft photonic crystals, we found that the resin can endure up to 2 tera watt/cm² of laser beam in the air environment.

**Figure 9.** Configuration of a Z-scan method to find out optical damage threshold and nonlinear absorption or nonlinear emission of photonic crystals.

### 5. Conclusion

We have proposed an industrial application of photonic crystals to high energy laser system aiming at peta watt scale and discussed their feasibilities. We are hoping to adopt those new photonic materials to resolve future energy problems such as lack of oil or Uranium for energy/electricity generation.

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