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REVIEW ARTICLE

Photonic crystals and microlasers fabricated with low refractive index material

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Although the investigation on photonic band gap materials has been done more than two decades, it is still a big challenge to fabricate three-dimensional photonic crystal (PC) possessing wide band gaps in visible range. In this article, we have reviewed recent progresses on fabricating the PC with low refractive index material in visible range. In contrast to the material with large refractive index, it is cheap to use low refractive index material in fabricating the PC and will be greatly beneficial for future industrial productions. The holographic method to fabricate such a PC has been introduced, applying it to the design of the microlaser has also been discussed.

Keywords photonic crystal, low refractive index material, band gap, microlaser

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Contents

1 Introduction

Since the pioneering work of Yablonovitch [1] and John [2], a significant effort has been devoted to the study of photonic crystal (PC) both theoretically and experimentally more than two decades. The PCs are regular arrays of material with different refractive indices, which are classified mainly into one-, two-, and three-dimensional (1-D, 2-D, and 3-D) structures according to the dimensionality of the stack [3–5]. Since the PCs can have spectral gaps in which electromagnetic wave propagation is forbidden in all directions, they offer the possibility of controlling the flow of photons in a way analogous to electrons in a semiconductor [1–5]. Thus, it can have profound implications for quantum optics, high-efficiency lasers, optoelectronic devices, and other areas of applications [6–9]. In contrast to the study of gaps in the PCs, wave transport in band regions can also exhibit some different properties in comparison with those in general homogeneous media due to remarkable dispersion properties. For example, supercollimation [10], superprism [11], and negative refraction [12–15] are some of the fascinating phenomena that strongly motivate the community at this time. Based on them, the PCs can also be used in designing new optical functionalities and novel devices.

The basis of the application for the PCs is to fabricate the materials. The first successful PC was fabricated in 1991 by Yablonovitch [16]. The crystal was fabricated by drilling three series of long slanted holes through the top surface of a solid dielectric slab. The intersection of the holes below the surface produced an intricate periodic network of intersecting holes. Since then, different fabricated methods, such as semiconductor microfabrication [16, 17], layer-by-layer [18, 19], microsphere self-assembly [20, 21], and laser holographic lithography technique [22, 23], have been developed. In contrast, the band gap of the electromagnetic wave in the PCs have been calculated by using various method, such as the plane wave expansion method (PWEM) [24–26], the transfer matrix method (TMM) [27, 28], the finite difference time domain method (FDTD) [29, 30], and the multiple scattering method (MSM) [31, 32]. For two decades, many photonic band gap structures have been successfully fabricated for frequencies in both microwave and near-infrared regions [21, 33–35], but it is still very difficult to fabricate 3-D PC possessing wide band gaps in visible range.

Holography is a cheap, rapid, convenient, and effective technique for fabricating 3-D structures in visible range. However, only some materials with low refractive index can be used for such a fabricating. According to some theoretical analyses [36–40], the complete band gap (CBG) can only appear in some PCs when the modulation of the refractive index of the material should be larger than 2.0. Then, the question is whether or not the PCs with the CBG can be obtained by using such a method? How can we obtain it? Recently, some progresses have been achieved in such a subject. In this article, we briefly review some advances in fabricating PCs with the low refractive index material in visible range by using holography. The property of microlaser based on such a PC has also been discussed.

2 The holographic method to fabricate PCs

In 1948, Gabor [41] proposed a method to record the amplitude and the phase of light, then experimentally confirmed the idea, i.e., holography, and produced the first hologram in the world. The superposition of several coherent laser beams will result in the interference pattern similar to a lattice structure in the coherent region. In addition, the lattice is originally used as an optical trap for bounding atoms. In the 1970s, Ashikin [42] first proposed that atoms or small particles can be cooled and captured in the optical potential well by the light field force. Subsequently, some experiments reported small particles can form a periodic arrangement in the submicro periodic light intensity distribution producing by multibeam interference [43–46]. However, the periodic structure will disappear if the laser field is removed. Therefore, such a method is not practical. To find a way to retain the periodic structure for a long time becomes a necessity. Soon, it was found that interference patterns can be recorded in the recording materials to create long term retention of the periodic structure. In other words, when N light beams intersect with specially designated angles, the interference pattern will appear in the superposed region. A recording plate is placed in the region to record the pattern. When the total light intensity at a position exceeds a specified threshold, the recording material at the position is chemically altered, and then, a periodic structure is fabricated.

In 1994, Petsas *et al.* [47] noticed that 3-D optical lattice can be produced by multibeam interference. One year later, Zhang *et al.* predicted [48] and realized [49] PCs using multibeam interference patterns. In 1997, holographic technique was introduced for fabricating a 2-D PC by Berger *et al.* [22], and a possible extension to 3-D structure was also proposed. In 1999, Kirkpatrick *et al.* [50] produced a strip grating microstructure using two-photon polymerization material to record the interference fringes of two beams of Ti: sapphire femtosecond laser, and the grating constant is 3.8 microns. In 2000, the 3-D structure with holographic lithography was fabricated successfully by Campbell *et al.* [23]. They recorded the interference pattern of four laser beams in the SU-8 photoresist material and used it as a template, and the template was inverted by infiltrated with SiO_2, then a 3-D PC was obtained. This is a big step forward in microproduction technology, enabling people to see the prospects and potential of laser holographic technology. Almost at the same time, Shoji *et al.* [51] fabricated a 3-D PC template using photopolymerization resin as the recording material by multibeam interference method. They first fabricated 2-D hexagonal structure by three-beam interference and then split the structure by standing wave field of two-beam interference and finally obtained a 3-D PC with the hexagonal structure. Later, a method, holographic lithography combined with laser-induced thermoplastification [52], is also proposed to fabricate permanent submicrometer periodic structures by interference laser fields.

When holography was just beginning to be introduced to produce PCs, there were three main shortcomings, i.e., holography involves lots of laser beams leading to instabilities in the optical setup and adjustment complexity of beam parameters, and the refractive index contrast of holographic recording materials is generally low. In recent years, some improvements in the process of holographic lithography have been done.

2.1 Simplification of holographic optical setup

Holographic method generally involves a large number of laser beams. In general, to obtain a 3-D intensity pattern, the number of light beams needs to be four or more. For example, four-beam configurations are needed to form an fcc structure (see Fig. 1). In Fig. 1, four beams separated from a laser beam were converged to a small area. The central beam was set along the normal direction of the surface of the plate, while the other three outer beams were set around the central beam symmetrically with an angle of 38.9° with respect to the central one. The holographic interference of multiple independent beams can introduce alignment complexity and inaccuracies, as well as vibrated instabilities in the optical setup. These problems can be solved by using a single refracting prism [33] [see Fig. 2(a)] or a single diffraction element mask [53] [see Fig. 2(b)]. The two optical components enable the splitting and recombining of a single incoming beam to form multiple-beam interference pattern simultaneously. Thus, antivibration equipment and complicated optical alignment system are not required.

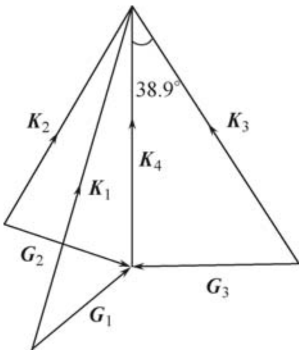

Fig. 1 Schematic optical layout for recording an face-centred cubic structure.

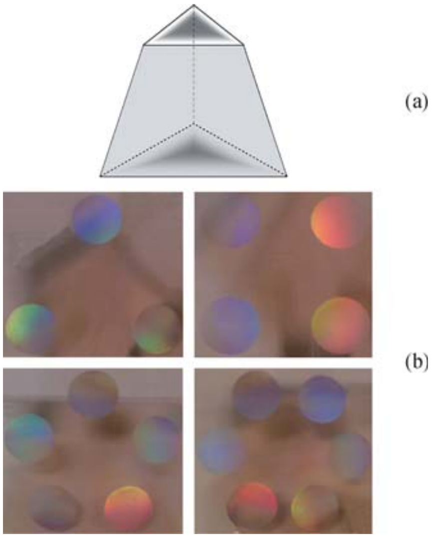

Fig. 2 Two kinds of optical components using in laser holographic lithography technique. **(a)** Single refracting prism; **(b)** Single diffraction element masks.

Berger *et al.* [22] used a diffractive optical element, which composed of three diffraction gratings, to split a beam by three gratings then recombined three first-order diffracted beams to create a 2-D PC. And they also proposed that 3-D PCs can be obtained in the same way. In 2001, Kondo *et al.* [54] split a beam into nine using a diffractive beam splitter and then chose five of them to form 3-D PCs. Later, they improved this method and produced 3-D PCs by multiphoton absorption using femtosecond laser interference [55]. Since the optical path difference is minimized, the method is especially suitable for the production of PCs with femtosecond pulses. In contrast, the advantages of the diffraction grating proposed by Berger *et al.* are low cost, more stable, using fewer optical components, ease to make, etc. Therefore, using diffractive gratings as a beam splitter is a good choice. In 2003, Divliansky *et al.* [53] fabricated a hexagonal PC using the diffractive grating with grating period of 1.0 and 0.56 µm. In the meantime, Liu *et al.* explored the possibility of improving this method [56, 57]. Schneider *et al.* [58] presented a method, which consists of three separate exposures, for fabricating 3-D PCs by interference lithography, capable of generating PCs lattices with lattice periods that can be controllably varied over a wide range. Using such a method, they successfully fabricated the Yablonovite structure for the first time by holography. In addition to two kinds of diffractive optical elements, Klein-Wiele *et al.* [59] proposed a beam spitting scheme with diffractive elements, and the phase relations among multiple beams can be controlled with almost arbitrary precision by changing the distance between the diffractive elements. The method has practical significance for studying the relationship between the phase and crystal structure.

In 2003, Miklyaev *et al.* [60] noticed that the fcc structure cannot be obtained by the method proposed by Campbell *et al.* [23], because the refraction at the air-photoresist interface made it impossible to obtain the required angles of the light wave vectors for making such a structure inside the photoresist. Therefore, they introduced a specially designed "prism" on top of the photoresist to successfully solve the refraction problem. That same year, Wang *et al.* [61] proposed a similar single refracting prism to avoid antivibration equipment and complicated optical alignment system.

2.2 Optimization of beam parameters of holographic method

The optimization of beam parameters involves many factors, such as the beam number, beam angle, beam intensity ratio, polarization, and phase and times of exposure.

The polarization direction of the linear polarized light will change after passing through a grating, which makes the symmetry of interference patterns change and the contrast decrease, thus affecting the production of the required PC structure in the photoresist. Therefore, how to select the angle between the polarization direction of the incident light and the grating vector and how to adjust the diffraction efficiency of the grating [62] to compensate the change of lattice structures and the reduction in contrast caused by changes of the polarization state are interesting issues worthy of further in-depth exploration. Cai *et al.* [63, 64] and Wang *et al.* [65] explored issues about adjusting independently the beam intensity, phase, and polarization more in-depth and proved that all 14 Bravais lattices can be formed by four-beam interference. Relevant theoretical simulation and exploration of holographic interference experiment have been under way [66–70].

One of the purposes is to find more structure that is suitable for holography and possesses sufficiently large band gaps. It has been predicted and verified experimentally that the diamond structure [39, 68, 71, 72], the woodpile structure [73–77], and the simple cubic structure [66], which is applicable to waveguide can be formed by multibeam interference, and both of them possesses wide band gaps [26, 73, 78]. The researchers in university of Toronto have also done a lot of work in looking for more holographic interference structure supporting wide band gaps [79].

On the other hand, it is necessary to explore more nontraditional structure type using holographic interference [48, 80–84]. Through adjusting the parameters (such as the beam polarization, beam number and times of exposure [85, 86], etc.) accurately, a variety of complex optical lattices have been achieved in experiments with holography, for example, complex lattices [87–90], quasicrystals [91–95], periodic quasicrystals [96], periodic complex photonic crystals constructed with a portion of photonic quasicrystals [97], Ag nanoparticles-embedded periodic and quasiperiodic microstructures [98], hetero-binary and honeycomb photonic crystals [99], coupled photonic crystal resonator arrays [100] and diverse metamaterial structures [101], etc.

In conclusion, holographic interference is very flexible. Theoretical studies have shown that almost all kind structures (1-D, 2-D, and 3-D) can be achieved by using the above method. Experimentally, many photonic structures have been obtained by such a method, such as period structures [see Fig. 3(a) and (e)], gradual period heterostructure [see Fig. 3(b) and (c)], circular structure [see Fig. 3(d)], and random structure [see Fig. 3(f)].

2.3 Improvement of holographic recording media

The most common holographic recording materials are photoresist (refractive index $n \approx 1.7$) and dichromated gelatin (DCG, $n \approx 1.5$). Both of them are low refractive materials. Generally, the CBG does not exist in PCs consisting of these low refractive materials.

Photoresist is a relief holographic recording material. To achieve CBGs in PCs made by the photoresist, i.e., to increase the refractive index contrast to 2 or more [36–40], there are two feasible solutions. i) PCs made by the photoresist can be used as templates for the production of inverse replica structures, for example, by filling the void with high refractive index and burning out or dissolving it [20, 23, 102–105] and ii) by doping metal nanoparticles in the photoresist [94, 106–109]. After the improvement, the PC will possess relatively high refractive index contrast to achieve CBGs.

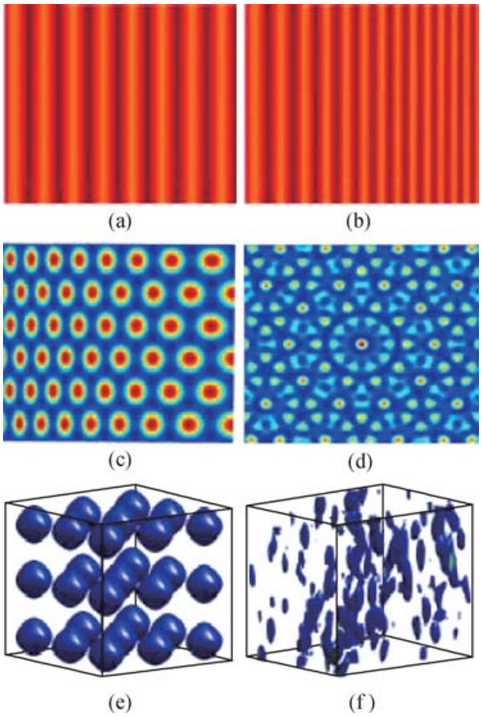

Fig. 3 Patterns formed by laser holographic lithography technique. **(a)** 1-D period structure; **(b)** 1-D gradual period photonic heterostructure; **(c)** 2-D gradual period photonic heterostructure; **(d)** Circular photonic structure; **(e)** 3-D period structure; **(f)** Random structure.

DCG is a phase holographic recording material. Recent researches show that the band gaps can appear in 1-D and 2-D PCs with low refractive index and gradient spacing [110, 111]. This is very interesting because it is not easy to find the materials with large refractive index, and the special techniques needed are very complicated and expensive. It limits the applications of the PCs, especially for industrial productions.

Overall, the advantages of holographic method are low cost, simple, defect-free, large-size, etc. Besides, the potential of mass-production of holographic PCs is also very attractive [75].

3 The properties of band gap in PCs with low refractive index material

3.1 The band characteristics of PCs made by photoresist

The dielectric constant of the photoresist is too low to warrant CBGs. However, there are also lots of interesting behaviors in the band characteristics of PCs made by the photoresist.

Wang *et al.* [112] reported that when the samples are

4–5 layers, two kinds of spectra are observed: one has a single peak (in the reflectance) with peak value changing somewhat with polymer volume fraction, and the other is more complicated with oscillating band gaps. They believed that the details of the structure and the volume fraction of the sample play an important role in the phenomena.

Chen *et al.* [113] presented a significant improvement to the reflection and transmission spectra from 3-D polymer PCs fabricated by holographic lithography. By optimizing the photoresist initiation system, they observed that the measured peak reflectance is 70%, which is significantly higher than that of typical fabricated crystals and only about 30% for common polymeric templates [33, 40, 104, 105, 114].

3.2 The band characteristics of PCs made by DCG

Compared with the photoresist, the DCG material has some advantages in forming photonic band gaps due to its unique material properties.

Liu *et al.* first provide analytical solution (AS) [115, 116] of wave transport in the PCs with low refractive index material (such as photopolymers [117], liquid [118, 119], or DCG [111, 120, 121]), and some unique properties can be seen clearly from the AS. From the detailed analysis of the AS [116], it can be seen that 2-D absolute band gaps (ABGs, band gaps for both TE and TM waves) cannot be achieved in the strict period PC structure with low refractive index materials. However, the band gaps can be obtained in nonperiodic optical heterostructures [see Fig. 3(b) and (c)] [122]. The gradual period of the heterostructure is an important factor for obtaining ABGs. For this kind of structure, the lattice constant changes gradually and linearly. According to the experimental conditions in Ref. [122], for the 2-D triangular lattice, there are 150 layers in the fabricated structure. They can be treated as 150 substructures. The upper band edge of the first substructure and the bottom band edge of the last (N=150) substructure determine the width of the total band gap of the heterostructure. Figure 4 shows the results calculated by PWEM. The dark gray zone is the common gaps of all directional gaps so that an ABG of the heterostructure is formed.

One of the characters of this kind of triangular lattice is that the bands of TE and TM waves are almost superimposed, and band gaps are close to each other along every direction. This character is very helpful for achieving ABGs through gradual period heterostructures, when the number of layers of the heterostructure is large enough and the expansion of the recording material reaches a certain range, a wider ABG will be obtained by use of narrow directional band gaps.

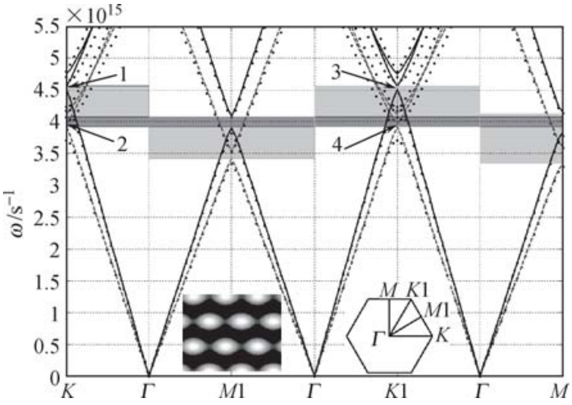

Fig. 4 Calculated dispersion relation of gradual triangular lattice heterostructure. The left iconograph at the bottom shows the lattice geometry. The right iconograph at the bottom shows the first Brillouin zone of the triangular lattice.

In 2006, Tam *et al.* reported that wide band gaps about 100 nm are obtained in the visible range for 1-D PCs with gradient spacing [110]. Moreover, similar results were obtained by Ren *et al.* [111]. The solid lines in Fig. 5(a) and (b) describe the experimental and numerical results of the transmission coefficient as a function of the frequency for such a system. Both of them show that the wide band gap appear around 500 nm. Subsequently, the ABG was observed experimentally in the corresponding 2-D gradual heterostructure by Zhai *et al.* [121]. Figure 6 displays the measured results. The width of the gap is about 70nm around the wavelength 470 nm.

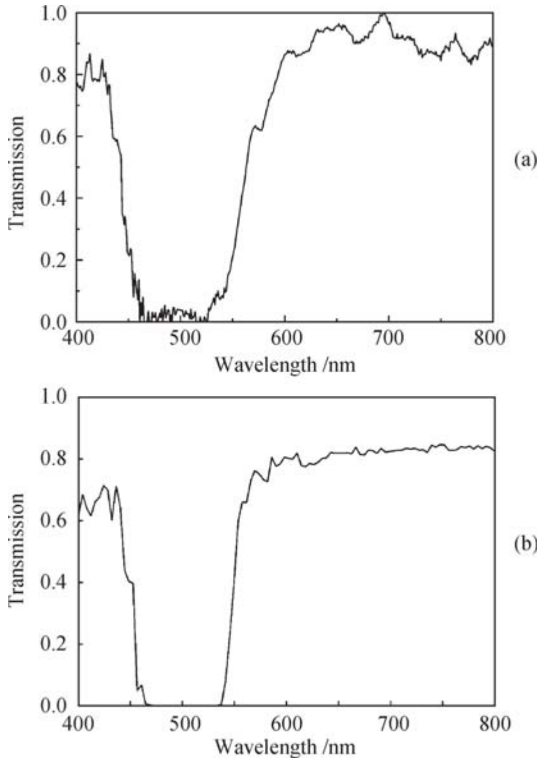

Fig. 5 Wide band gap in 1-D photonic crystals with gradual period. **(a)** Experimental results; **(b)** Simulation results.

However, the CBGs in 3-D holographic PCs with low

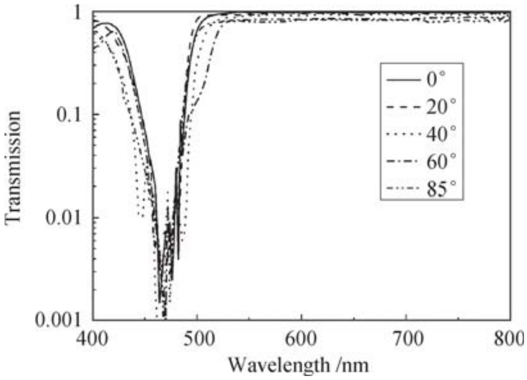

Fig. 6 Transmission spectra of a gradual heterostructure as shown in Fig. 3(c).

refractive index materials have not yet been reported so far. Besides gradual heterostructure, multiperiod structures have also attracted people's attention. In 2007, a holographic method was proposed to fabricate complex diamond lattice using materials with low refractive index [120]. It is known that a cell of diamond structure consists of two cells of fcc structures, and the two cells have a distance of one quarter of the diagonal length of the cell along the diagonal line. Considering that there are several directions with high symmetry in the first Brillouin zone of an fcc structure, two exposures were made first in Γ–L ([1 1 1]) direction to get a diamond structure. Then, a second and a third diamond structure was implemented by changing the orientation of the recording material through rotating the rotary stage to other symmetric directions, i.e., the direction of Γ–X ([1 0 0]) and the direction of Γ–K ([1 1 0]) in the first Brillouin zone of the first fcc structure. In this way, PCs with three diamond structures were fabricated. By this method, very wide band gaps were obtained experimentally. The width of the band gaps reached 260 nm; the ratio between the width and the central wavelength of the gaps reached 50%, as shown in Fig. 7 (the measured transmission spectra of PC with three diamond lattices recorded by holography in Γ–L, Γ–X, and Γ–K directions of an fcc lattice, respectively). Also, a common gap was observed in the range of 150° of incident angle in [1 1 1] plane at all orientations. This kind of complex-diamond lattice is greatly beneficial for obtaining CBGs.

Although a CBG has not been found in the above 3-D structure realized by multibeam interference, it can appear in a self-similar spherical structure with the low refractive index. This kind of structure has been implemented by Ren *et al.* in terms of holography [111]. The schematic of the structure and fabricating process are shown in Fig. 8. This includes three steps: i) preparation of the recording material by coating the emulsion on a soft substrate; ii) fabrication of 1-D PC in rectangular coordinates by using this recording material [Fig. 8(c)]; and iii) making this PC into a sphere [Fig. 8(a)]. In this way, a 1-D PC in rectangular coordinates was transformed to a spherical 1-D PC system. The measured

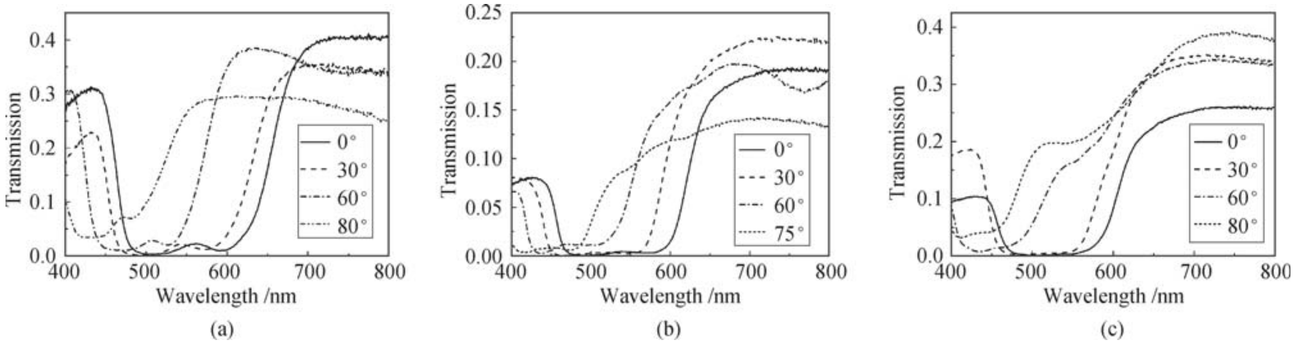

Fig. 7 Measured transmission spectra of photonic crystals with three diamond lattices recorded by holography in Γ–L, Γ–X, and Γ–K directions of an face-centred cubic lattice respectively. (a), (b), and (c) correspond to the measured results. The angles appearing in (a), (b), and (c) are the incident angles, which are in a plane parallel to the surface of the paper. **(a)** Orientation angle is 0°; **(b)** Orientation angle is 30°; **(c)** Orientation angle is 90°.

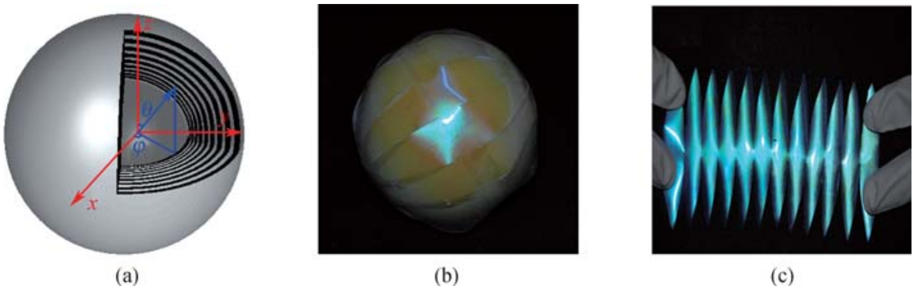

Fig. 8 Self-similar spherical structure. **(a)** Schematic of a self-similar spherical structure (ϕ and θ are the azimuth angle and the pitch angle in spherical coordinate respectively). **(b)** Photographs of photonic crystal in self-similar spherical structure and **(c)** a cut piece of one-dimensional photonic crystals in rectangular coordinates.

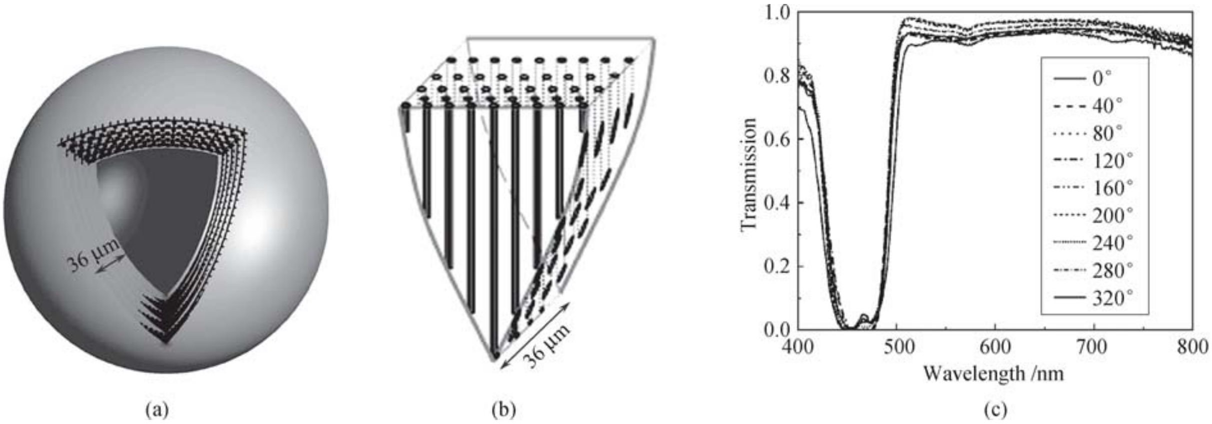

Fig. 9 Structure of D_{nV} point group and its transmission. **(a)** Schematic diagram of D_{nV} self-simulating sphere structure; **(b)** The schematic diagram of the cut slice of the sphere shown in (a); **(c)** transmission spectra of the spherical structure.

transmission and reflection spectra around the center of the sample revealed that a true CBG actually exists for this kind of structure. However, there are two disadvantages about this spherical structure: i) When the working condition has a relative large deviation from ideal conditions, the CBGs disappear; ii) The size of the spherical structure is too big, so it is not suitable for integration.

One year later, both problems mentioned above were solved. A structure with D_{nV} point group was fabricated by compounding a gradual heterostructure and a self-simulating sphere [121]. The gradual heterostructure has 2-D ABG, and the self-simulating sphere makes it possess a CBG. This new type spherical structure possesses real CBG (See Fig. 9) in a discretionary condition. In addition, a miniversion of the self-similar spherical structure is successfully fabricated by Hung *et al.* [123]. They have fabricated spherical layer structures that exhibit the CBGs in the visible range in DCG by holographic interference. The CBG was not a result of the high dielectric contrast but was due to the fact that the spherical layer structure was isotropic with equal spacing in all accessible directions.

4 Microlaser realized by low refractive index material

In recent years, there has been a great deal of interests in studying different types of lasers made by the PC [124–134]. One kind of the PC-based lasers can occur without external feedback, which the standing wave solution of the Bloch waves at the band edge can be regarded as the feedback source. Such kind of laser has been investigated extensively [127–134]. However, all previous works focus on the PC with high refractive index material. Recently, achieving lasing by low refractive index material has been proposed.

In 2008, Kok *et al.* [133] first reported on optically pumped lasing from dye-doped, graded-spacing layer structures of DCG fabricated using two-beam holographic interference. Multimode lasing with both a low threshold and a high-quality factor was observed at the band edge of the photonic band gap.

In 2009, Kok *et al.* [134] found that quasicrystals are more efficient in providing the feedback mechanism for lasing because quasicrystals have higher symmetry and are more favorable for the formation of photonic bandgaps. In addition, they reported observation of lasing at visible wavelengths from dye-doped 3-D icosahedral quasicrystals fabricated in DCG using a seven-beam optical interference holographic method. The multidirectional lasing exhibiting the icosahedral symmetry was observed.

In fact, the laser action is not only realized in periodic and quasi-periodic structures, it is also observed in other nonperiodic structures. Recently, we introduce another type of laser without external feedback by using the low refractive index material, the circular photonic crystal laser (CPCL) [135]. The circular photonic crystal (CPC) is different from those periodic and quasi-periodic PC. The lattice arrangement in the CPC structure is the same as that of ring structures in microstructured optical fibers, as shown in Fig. 10(a) [135]. The CPC possesses $2\pi/m$ rotational symmetry, where m is the rotational fold number.

If the dye molecules are introduced in the CPC, the multimode lasing with both a low threshold and a high-quality factor can also be observed. The black circle line in Fig. 10(b) corresponds to the (photoluminescence) PL spectra of Rhodamine 6G, and the red solid line represents the emission of the dye-doped CPC sample at certain incident angle. It can be seen clearly that more than four lasing modes are excited in the gain spectrum of Rhodamine 6G. Due to the isotropic photonic band gap effect in the CPC, the intrinsic feedback at the band edge provided by such a CPC structure is independent on the directions, which leads to better lasing properties

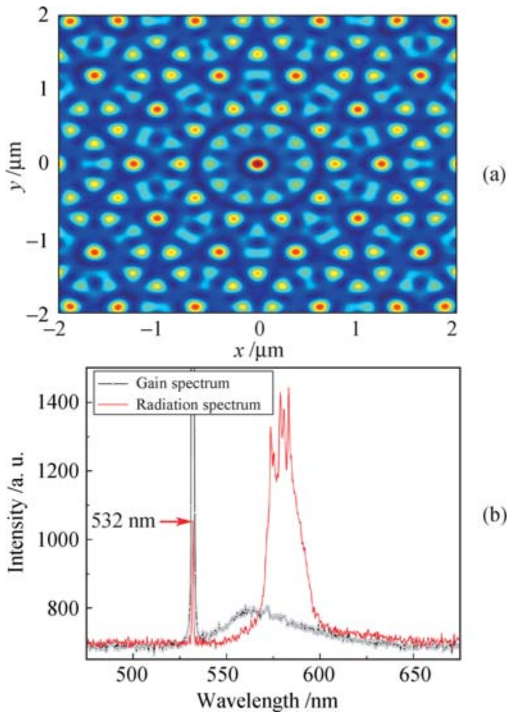

Fig. 10 **(a)** Structure of 2-D photonic crystal fabricated by multi-beam interference. **(b)** The PL spectra as a function of the wavelength at $\theta \approx 30°$. Red line corresponds to the emission of dye-doped CPC sample, and black circle line to the gain spectra of Rhodamine 6G. The pumping intensity is 127.3 MW/mm^2.

with the isotropy. The isotropic properties of the laser action in the present structure are better than those in the quasi-periodic structures.

Not only can the periodic or quasi-periodic structure be fabricated by holographic method but also can the random system be realized by using such a method. Figure 11(a) describes the set-up geometry of the disorder structure formed by speckle. A ground glass was used to generate spatial speckle structure. A reference beam was introduced to implement interference for recording the distribution of the spatial speckle in the holographic recording material. Different distribution of the spatial speckle can be recorded by changing the place of the ground glass or the reference beam. The microscopic images of the disordered system formed by the speckle are shown in Fig. 11(b) and (c). This is a weak scattering system because the mean free path is much larger than the thickness of the system. However, if the gain is introduced in the system, the random laser can be observed [136].

Figure 12(a) and (b) display the measured results for the emission spectra under the pump by picosecond and nanosecond lasers, respectively. A single mode is observed, and the profile of the mode is fitted by a Gaussian function for the case of nanosecond excitation, while the multimode lasing is found in the case of picosecond excitation. This means that two kinds of feedback for the random lasing, coherent and incoherent, can be observed experimentally for the same sample.

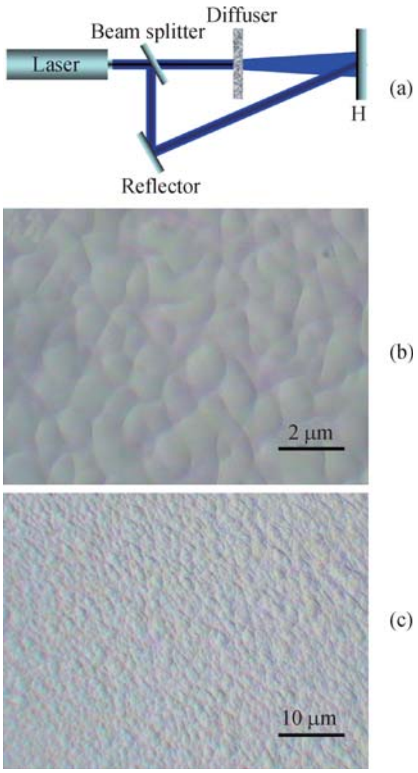

Fig. 11 **(a)** Set-up geometry of the disorder structure formed by speckle. H is holographic recording material. **(b)** and **(c)** are the microscopic images of the disordered structure formed by speckle.

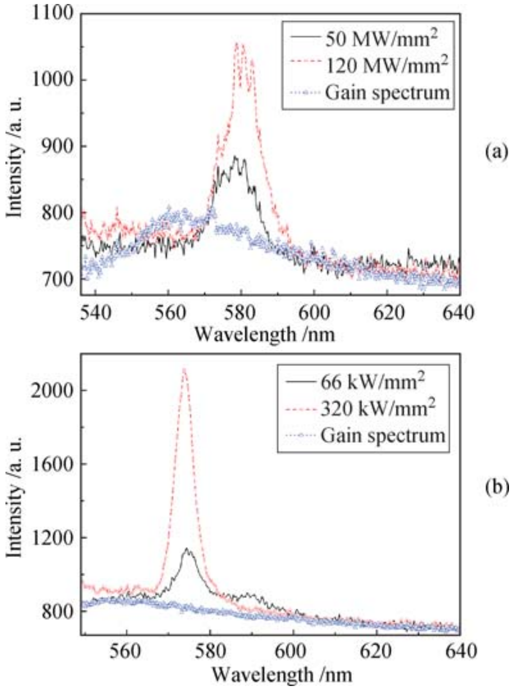

Fig. 12 **(a)** Set-up geometry for measuring random lasing. θ is the angle of the pump beam with respect to the surface of the substrate, it represents the orientation of the sample. **(b)** Emission pumped by ps laser, and the inset shows the threshold is about 50 MW/mm^2 at $\theta = 25°$. **(c)** Emision pumped by ns laser at $\theta = 30°$. In (b) and (c), the blue triangles are the gain spectrum of rhodamine 6G excited by 532 nm laser beam. The black solid line and the red dashed line represent the emissions with pumped energy around and much higher than threshold respectively.

Another interesting phenomenon for the present system is that the emission wavelength for the random laser can be tuned through changing temperature. Figure 13 shows the measured spectra of lasing emission at different temperatures. It can be seen clearly that the emission peaks shift toward the long wavelength with the increase of the temperature, which benefits some applications, such as remote temperature sensing in hostile environments.

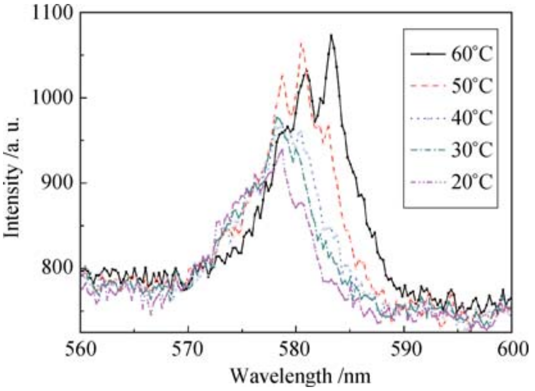

Fig. 13 Tunability of wavelength vs. temperature of the random laser.

5 Summary

Based on a series of our researches, in this brief review, we have described the recent progresses on fabricating the PC with low refractive index material in visible range by holography. The history of research related to holographic technique to fabricate the PC has been summarized. The properties of band gap in the PC with low refractive index material have been analyzed. The microlasers realized by such a kind of the PC and random medium have also been discussed. In contrast to the material with large refractive index, it is cheap to use low refractive index material in fabricating the PC and will be greatly beneficial for future industrial productions.

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