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全像三維光子晶體研製

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We present the brief report in the following 4 major Sections:

I. Publications:

1.1 Journal Papers

X. L. Yang, L. Z. Cai, and Q. Liu, Hua-Kuang Liu(劉華光), "Theoretical band-gap modeling of two-dimensional square photonic crystals fabricated by the interference of three non-coplanar laser beams", accepted for publication by JOSA B and will appear in 2004.

Chia-Wei Sun, Kuei-Chao Liu, Yih-Ming Wang, Hsiang-Hsu Wang, Yean-Woei Kiang, Hua-Kuang Liu (劉華光) , C. C. Yang, "Determination of target depth in a turbid medium with polarization-dependent transmitted signals," JOSA A, **20,** (11), 2106-2122(2003).

L. G. Deng and H. K. Liu (劉華光) , "Nonlinear optical limiting of the azo dye methylred doped nematic liquid crystalline films," Optical Engineering, **42**(10), 2936-2941(2003).

1-2 Invited Oral Presentations

- *Hua-Kuang Liu (*劉華光) and Tze-Min Yan (顏子旻), "Holographic Creation of 3-D Photonic Crystals via Multiple Beam-Splitting Holographic Optical Elements", An invited paper presented at the "Workshop on Advanced Photonic-crystal Devices at the Institute of Electro-Optical Science and Technology, National Normal University, Taipei, Taiwan, October 18-19, 2003.
- *Hua-Kuang Liu (*劉華光), Tze-Min Yan (顏子旻), and Han-Tsung Hsueh (薛翰聰),
"Holographic photonic crystals for increasing external quantum light efficiency in organic light emitting devices", an invited paper presented at the Solid State Lighting Forum, National Central University, Chungli, Taiwan, January 8, 2004.
- *Hua-Kuang Liu (*劉華光) and Tze-Min Yan (顏子旻), "Optical Holography and Its Applications for the Generation of Photonic Crystals", An invited paper presented at the Graduate Colloquium, Physics Department, Dec. 29, 2003.
- *Hua-Kuang Liu (*劉華光) and Tze-Min Yan (顏子旻), "Two Different Approaches for the Creation of General Photonic Crystals via Holographic Interferometry", An invited paper to be presented at the 2003 Annual Meeting of the Optical Engineering Society, Taipei, Taiwan.

II. 研究計畫之背景、目的、重要性及國內外有關本計畫之研究情況、重要參考文獻之評述等。

The objective of this proposal is to adopt a new holographic technique for creation of 3-D periodical nanometer structures or photonic crystals by interference of multiple non-coplanar beams and to analyze the resulting bandgap structures for engineering applications.

The engineering applications of photonic band structures include microwave transmission guides and antennas, and quantum electrodynamics' devices using atoms and molecules. The photonic structure associated with line defects (waveguides) and point defects (micro cavities) will provide basic ingredients for controlling spontaneous emission of atoms in materials for many optoelectronics devices. Waveguides in photonic crystals will provide a unique ability for guiding optical light in air, along narrow channels and around very tight bends, with little loss. Microcavities in photonic crystals will provide complete tunability in both defect frequency and symmetry. The flexibility in tuning the symmetry, frequency and localization properties of defects makes photonic crystals a very attractive medium for the design of novel types of filters, couplers, low threshold semiconductor lasers and single-mode light-emitting diodes (LEDs).

Photonic crystals refer to bandgap structure in which the dielectric constant is periodically modulated on a length scale comparable to the desired wavelength of operation. The periodic arrangement of ions on a lattice gives rise to the energy band structure in semiconductors. Energy bands control the motion of charge carriers through the crystal. Similarly, in a photonic crystal, the periodic arrangement of refractive index variation controls how photons are able to move through the crystal. Replacing the ions on a lattice are regions of low refractive index within a high-refractive index material or vice-versa. Photons react to the refractive index contrast in an analogous manner to the way electrons react when confronted with a periodic potential of ions. Each results in a range of allowed energies and a band structure characterized by an energy gap or photonic band gap. A band gap forms when the electron wavelength is comparable to the inter-atomic spacing.

The study of photonic crystals is a promising area in nanotech and modern optics.[1-2] Photonic bandgap structure is poised to meet the needs for high-bandwidth communication network and optically connected computing for switching, multiplexing, interconnects and efficient laser sources. For instance, to show the interests and importance of this area, selected recent and relevant journal articles on the band gap structures is listed in the appendix.

Photonic band gaps were first predicted in 1987 independently by Eli Yablonovitch and Sajeev John. An array of 1mm holes milled into a slab of material of refractive index 3.6 was found to prevent microwaves from propagating in any direction. An estimate of the distance between voids is given by the wavelength of the light divided by the refractive index of the material. This relationship means that it is even more difficult to create photonic crystals in materials with high refractive index. Finding materials and techniques of producing photonic crystals has remained illusive until 1997.

Breaking the periodicity of the voids in the photonic crystal, either by enlarging or reducing the size of a few of the voids, introduces new energy levels within the photonic band gap. This is analogous to the creation of energy levels within the band gap by the addition of doping atoms in semiconductor crystals. Narrow line width lasers, that are so important in the area of Dense Wavelength Division Multiplexing (DWDM) communication systems, can be fabricated using photonic crystals formed from the III-V semiconductors or rare-earth doped glass. The defect mode or micro cavities formed by breaking the periodicity of the crystal amplify only those wavelengths of light those are able to pass freely through the crystal. The wavelength range of emission is related to the diameter of the micro cavity divided by the diameter of the regular holes. Photonic crystal micro cavities are more efficient than conventional semiconductor diode lasers since there are few directions the photons can escape.

In passive devices, such as optical filters, where it is often required to filter a weak signal, the aim is to minimize further loss. Unfortunately, these losses are greater in materials with a high refractive index and photonic crystals use the contrast in refractive index to create energy band gaps. Altering the geometry of the voids, in such a way as to increase the symmetry of the periodic structure, the band gap can be restored in a low refractive index material. For example, by going from a rectangular array of voids in which the spacing of the holes is different for the two perpendicular directions within the plane, to a triangular arrangement which has a six fold degree of symmetry within the plane. A quasi-periodic arrangement of holes has a photonic band gap what ever the angle of the light travels.

Photonic crystals are also being exploited in the technology of optical fibers by Phillip Russell and Jonathan Knight et al. to create fibers that are carry light at high powers. Traditional optical fibers have a glass core surrounded by a cladding layer. The cladding has a lower refractive index than the core. The difference in the refractive index between the two materials is slight, but it is enough to cause light within the core to be reflected along the core by total internal reflection. At high powers, the light is concentrated in a very small region of space. Raman scattering can result, causing the light signal to be corrupted and at high powers the fiber can even be damaged.

The first photonic crystal fibers used a hexagonal array of air holes running the entire length of the fiber. These photonic crystal fibers are made by stacking pure silica tubes in a hexagonal array, and then heating and stretching it. This reduces the width of the structure, while retaining the geometry. The light traveled close to the fiber axis and so the power was still limited. Removing the central tubes leaves a central hole of 1.5mm in diameter which acts as a waveguide. The light is trapped by the photonic crystal structure around the hole. The photonic crystal allows only some of the light to propagate along the fiber. Ultimately, Phillip Russell sees hollow-core fibers as the basis of ultra high-power fiber-delivery systems, in which light from a powerful laser source is delivered to a cutting head in surgery and machining. And one day soon, hollow-core fiber might guide atoms or particles over long distances, forming the basis of fiber-optic devices that move matter.

In developing photonic crystals, the researchers have a dream to create a highly integrated micro-photonic device on a chip that can produce, switch, process light and send it to various optical interconnects, thus eliminating the need for copper or aluminum circuit connections. Over the past 15 years, basic photonic crystal structures operating in infrared and optical wavelengths have been theoretically investigated and experimentally realized. The new challenges in making passive and active photonic bandgap devices are many. For one, new directions must now be set to understand fundamental photon-matter interactions and thus realize active photonic components such as lasers, optical amplifiers and optical switches for system applications.

Particularly, it has always been a challenge to fabricate and understand 3-D photonic crystals and develop their engineering applications. The previously available methods of making 3-D periodic microstructure include semiconductor microfabrication,[3] colloidal crystallization,[4] tightly focused laser beam scanning,[5] and two-photon photopolymerization.[6] However, these methods are either too complicated or can only produce 1-D and 2-D photonic crystals.

Finally, in concluding the above background discussions, we answer two key questions.

(1) What is the importance of working on this topic?

Since the photonic crystals can produce photonic bandgaps and can guide and manipulate the propagation of light, these crystals have demonstrated attractive potentials in 3-D ultra-high capacity data storage, polymer waveguides, fiber communication, and other related fields. One of our applications is to fabricate photonic crystals on organic light emitting devices (OLED) and LEDs for increasing their external light emission efficiencies. The fabrication method is quite challenging. However, we have found new approaches and will test them in the proposed work. Breakthroughs in the proposed would be of great importance and interest to illumination and display in particular and nanotechnology in general.

(2) What's new in our approach?

Although holography is a well-developed subject, almost all the techniques previously available deal only with the interference of coplanar beams, but our approach is to use non-coplanar beams in a holographic optical element based multi-channel counter-propagating architecture. We also plan to generate various defects in the system by changing the angle or wavelength of the beams in the system or pre-deposit point or line defects into the recording media to form 3-D photonic crystal devices. The interference of multiple non-coplanar beams in the creation of 3-D photonic crystals, particularly when using pulsed laser, raises two special questions. One is the coherence requirement for all the beams. It means that all the beams should be exactly in phase at the sample. To solve this problem, our system is arranged in such a manner that nearly equal optical path length for all the beams. The second challenge is the polarization selection of each beam to obtain best uniform contrast. We have made a comprehensive study on this question and found an algorithm for this purposal[9,13]. Our optical architecture also ensures that the vertical polarization of the beams is essentially preserved.

III. 參考文獻

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IV. Potential Impact of the Holographic Crystals on Lighting and Display

The work proposed herein may have practical applications in increasing the light output of organic light emitting devices (OLED) for future lighting and display industries.

The low light output efficiency of OLEDs is a main obstacle for these devices to be effectively used for lighting and display applications. Existing methods used for the increase of the output efficiency include the use of micro lens arrays of higher refractive index on glass substrate and other substrates and the rectangular grating-type photonic crystal on the substrate. The emission models for the OLEDs include the point source emission model, the half-space dipole emission model, and the combined classical and quantum mechanical micro-cavity model. We can design a new holographic photonic crystal for increasing the output light emitting efficiency. The design principle of the holographic photonic crystal is based on the diffraction nature of light emitted from the organic layers of thicknesses around 100 nm which is much less than the emitting wavelength. We can design masks that simulate the emitting sources and fabricate the diffractive holographic photonic crystals via the interference of these light sources with a forward propagating plane wave. The advantages of the technique include the one-step fabrication and the minimum requirement of laser coherence. A variety of lasers and recording media may be used to fabricate the photonic crystals. If we use volume phase holographic recording media to fabricate the photonic crystals and position them on the output surface of the OLED, high efficiency beam shaping actions may take place and high output coupling of light will result.