Holographic Photonic Structures

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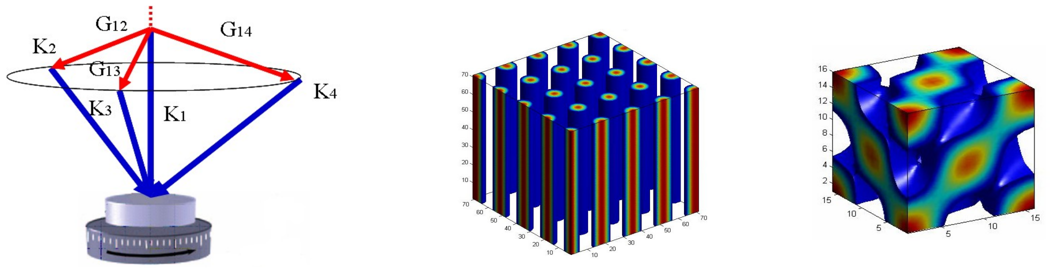
Holography which involves the recording and reconstruction of complex interferograms, is a very useful tool with potential applications in many areas. A digital holographic disk (DHD), employing holographic principles for the storage and retrieval of huge amounts of data at fast parallel transfer rates is envisaged as the next generation removable storage device after the DVD and Blue Ray-DVD. Holographic data storage offers storage capacities to the order of many Terabytes on a disk. A holographic storage disk can support a transfer rates in Gb per second in comparison to current technology's few Mb per second. These features have been achieved by the page-oriented storage principle and the multiplexing of a large number of such data pages in a single location. In addition to conventional address-based read-out, DHD offers the potential for simultaneous search of an entire database by performing multiple optical correlations between the stored data pages and a search argument. Such an added feature of content-addressable searching is always beneficial considering the high storage density of 500 Gbytes in 120 mm disk with VHDS. Since a holographic search engine performs an entire database search with a single optical exposure, it can potentially search massive databases orders of magnitude faster than conventional alternatives [1-5].

Another recent application of holography is, to use it as a tool to fabricate large area nano-photonic structures. Nano-photonics promises captivating new fundamental physics, and new applications in low power, ultra-small devices performing at the quantum edge in a wide range of technologies such as information processing, telecommunications, medicine and biotechnologies. Holographic technique has great potential in forming 2-D as well as 3-D volumetric structures in photosensitive materials. Photonic crystal structure requires a high contrast volumetric pattern. In holographic lithography, a periodic intensity distribution is produced with the help of 2 or more collimated beams [Fig. 1]. A photosensitive material such as photoresist or photopolymer is exposed to that intensity distribution. Post-exposure processing imposes a threshold on the smoothly-varying intensity contours in the interference pattern. Usually, photoresist is used as a recording material and after development the recorded structure is transferred to a high refractive index material, such as Silicon. Even though the fabrication of photonic structures on relevant length scales (i.e., nanometer, sub micrometer, and micrometer) can be achieved by means of various techniques such as electron or ion beam writing, deposition methods and self assembly, the prime advantage of holographic lithography is to fabricate large area defect-free nano-photonic structures both rapidly and cheaply [6,7].



Recording geometry

2-D and 3-D Photonic crystal structures

Fig. 1: Holographic recording geometry and photonic structures

We have developed novel methods based on two-beam and multiple beam interference having potential to realize any of the crystal lattice structures including diamond structures. Also presented are designs of fabrication techniques which are least complex and provide more flexibility compared to existing techniques. Simulations of the technique have been done using MATLAB and the potentiality of the techniques are experimentally verified by recording many photonic structures on photorefractive material.

We have shown that, by the interference of multiple beams as well as by the multiple exposure of two beam interference, all fourteen 3D Bravais lattices can be generated [8-10]. Photonic band gap (PBG) being the characteristic property of technological interest, engineering the PBG to make it tunable as per application requirement is of prime importance. Basically, for a given type of lattice symmetry, the PBG primarily depends on the form of the basis, and the dielectric contrast. PBG structures infiltrated with high refractive index materials like Si (n~3.5) in low refractive index photoresist (n~1.6) based holographic templates, is a versatile approach to achieve large volume 3D PBG structures with high refractive index contrast. Effective refractive index can be engineered by means of varying filling fraction of the basis structures of holographic templates, which in turn can be used for the realization of optimized large band gap back-filled PBG structures. It has been shown that the shape and size of the equal intensity surfaces of the holographic PBG structures are highly dependent on the choice of the filling factor, and therefore on the threshold intensity.

We have investigated by computer simulations, the influence of the threshold intensity on tuning the backfilled 3D PBG structures in holographic photonic templates. For the formation of holographic templates, we use a simplified DBME approach [6]. The approach involves only a single axis rotation of the recording sample, for the formation of 3D holographic templates with varying basis structures. The study included computer simulations of 3D holographic templates belonging to the fcc Bravais lattice, for varying threshold intensity leading to variable fill factor, and thus modulating the basis structure. PBG simulations for back-filled fcc lattice structure with high refractive index, by means of Plane Wave Expansion (PWE) method were carried out, verifying the influence of varying basis structure on the band gap of the back-filled PBG structures for the desired choice of the PBG for various photonic applications.

Based on the approach, high quality 3D holographic templates belonging to the desired lattice structure can be fabricated with a simplified experimental set up. The fill-factor of fabricated holographic structures can be tailored by means of proper choice of the threshold intensity. Fig.2 gives the simulated intensity distribution of interference pattern for the fabrication of fcc photonic template structures in photoresist (n=1.6). Here the x-y plane of the simulated structures is the (111) crystallographic plane of fcc lattice. Beams are considered to be launched to the recording material with an angle 38.9º between them. Once the design parameters for a particular lattice structure are calculated, the volumetric basis structure can be modified for a desired fill factor by varying the threshold intensity. The simulated structures of fcc lattice for varying threshold intensity in a normalized scale from 0.6 to 0.8, are given in Fig. 2. During the post exposure process, for example, the portion of a negative photoresist affected by the intensity $I < I_t$, where I_t is the threshold intensity, is etched out. So the fill factor in the template reduces as the threshold intensity is increased. At the mean time, in the subsequent process, the fill factor of the inverted back-filled structure would increase [6].

Nonlinear photonic lattices formed by a periodic modulation of the refractive index in nonlinear optical media are subject of active research due to their versatile promising applications. In view of fascinating nonlinear effects like discrete spatio-temporal solitons and quantum tunneling, based on the interplay of nonlinearity and various lattice geometries as well as periodicities, different approaches are adapted to form two-dimensional (2D) photonic lattices, most often in nonlinear photorefractive media. However, 3D reconfigurable photo-refractive photonic structures that are able to show advanced nonlinear features like slow and stopped light have not yet been realized.

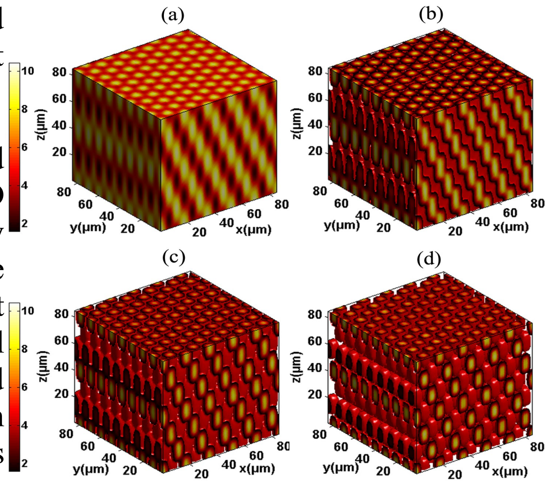


Fig. 2 fcc photonic structure showing the effect of thresholding

We have demonstrated the fabrication and analysis of well-defined reconfigurable 3D photorefractive nonlinear photonic lattices in externally biased Cerium doped Strontium-Barium-Niobate (SBN:Ce) photorefractive material by a spatial light modulator (SLM)-assisted versatile single step optical induction approach by means of computer engineered phase patterns. Unlike conventional multiple beam interference, where a complicated optical setup needs to be implemented, recently, actual techniques make use of discrete diffractive optical elements, single prism based approach or spatial light modulator assisted approach. Taking advantage of the wavelength sensitivity of a particular photorefractive media, optically-induced photonic lattices can be generated at very low power levels. Making use of the versatility of programmable SLM, based on computer-generated reconfigurable phase engineered patterns, we have simplified the conventional multiple beam interference technique for 3D photonic structures. The computer engineered phase pattern, representing the phase information extracted from the over all complex amplitude of the irradiation profile of the interference pattern for a particular 3D photonic lattice structure, is sent to a programmable phase only SLM. This phase engineered pattern spatially modulates a plane wave incident on the SLM, generating the required lattice-forming beams. Various 3D lattice-forming geometries for different reconfigurable 3D periodic lattices with variable periodicity are experimentally investigated in real time by this versatile approach. In order to exploit the full potential of the approach, the experimental realization of 3D hexagonal photonic lattices through our SLM-assisted optical induction approach is presented, where the lattice beam geometry consists of a normally incident central beam surrounded by angularly displaced six side beams.

Simulation and Experimental approaches used

The irradiance profile of $(n+1)$ plane wave-interference is given by,

$$\mathrm{I}(\mathbf{r}) = \sum_{j=1}^{n+1} \left|\mathbf{E}_j\right|^2 + \sum_{i<j}^{n+1} \mathbf{E}_i \cdot \mathbf{E}_j \exp[\mathrm{i}(\mathbf{k}_i - \mathbf{k}_j)\cdot \mathbf{r} + \mathrm{i}(\psi_i - \psi_j)]$$

where $\mathbf{E}i$, $\mathbf{k}i$, $\mathbf{r}$ and ψi are respectively complex amplitudes, wave vectors, position vector and the initial phase of the interfering beams. The interfering beams are linearly polarized in the direction relative to the crystal c-axis of the recording photorefractive medium oriented as per the lattice orientation requirement. The central beam is incident normal to the x-y plane of the recording medium. The phase patterns, which are sent to a phase only spatial light modulator (SLM)for generating the lattice forming beams, are simulated by computing the phase from the overall complex amplitude. Schematic of the experimental setup used is given in Fig. 3.

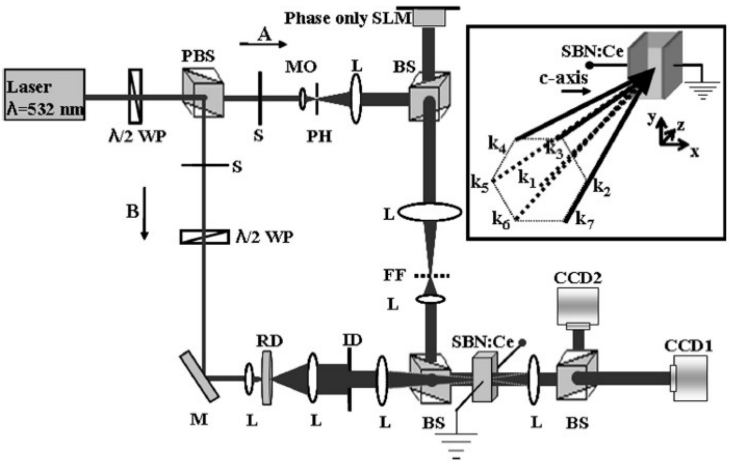


Fig. 3: Schematic of experimental setup

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