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Optically induced photonic superlattices by holographic multiplexing

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Abstract
We present an efficient method for optical induction of photonic superlattices in photorefractive media via holographic multiplexing. By superimposing phase engineered periodic waves of different periodicities, incremental recording of one- and two-dimensional multiperiodic lattices is demonstrated. The induced structures are subsequently analysed in Fourier space as well as in real space to verify the existence of multiple band gaps in the linear transmission spectrum.

1. Introduction

Due to versatile steering and control possibilities, wave propagation in nonlinear periodic structures has been the subject of extensive studies for several years. The interplay between periodicity and nonlinearity has been shown to cause a variety of fascinating nonlinear effects. In particular, discrete and gap spatial solitons have been studied in many different systems such as conjugated polymers [1], Bose Einstein condensates [2] and nonlinear waveguide arrays [3].

In optics, the induction of periodic refractive index structures in photorefractive materials [4] has been utilized to demonstrate a large variety of nonlinear localization effects such as soliton trains [5], Zener tunnelling and Bloch oscillations [6] as well as vortex solitons [7–9]. The advantage of this induction technique is given by the electro-optic properties of photorefractive crystals such as strontium barium niobate (SBN). They allow nonlinear, reconfigurable refractive index patterns to be achieved at very low power levels.

While in the past only comparatively simple geometries such as diamond, square [4, 10, 11] or hexagonal [12] lattices were studied, currently, special attention is paid to more complex photonic structures such as modulated waveguide arrays [13], lattice interfaces [14] or double-periodic one-dimensional photonic lattices [15]. The latter were realized by combining a permanent one-dimensional waveguide array and an additional, optically induced photonic lattice.

In general, such multiperiodic structures are of great interest since they offer many exciting possibilities to engineer the diffraction properties of light by opening additional mini gaps in the transmission spectrum and thereby facilitate the existence of new soliton families in nonlinear media [16].

In this paper, we present a new approach for all optical induction of multiperiodic superlattices by superposition of several single periodic lattices. The demonstrated method is closely related to the incremental recording in holographic data storage [17] and enables the induction of reconfigurable multiperiodic structures in one and two dimensions.

2. Optically induced photonic superlattices

A simple and well-known procedure to generate a desired intensity distribution for optical induction of photonic lattices in photorefractive crystals utilizes the interference of several plane waves inside the media. The periodicity of the induced patterns can be controlled by the interference angle whereas the modulation depth depends on the intensity of the interfering waves.

More flexibility in changing the lattice parameters can be achieved by using a programmable spatial light modulator to create the diffraction free propagating transversely periodic lattice wave [10, 11]. In fact, this configuration has been used to show the existence of discrete and dipole-mode gap solitons in photonic lattices of triangular shape [18] which would otherwise require the use of six plane waves and is consequently not very convenient to be induced by interference.

Unfortunately, for the induction of multiperiodic lattices the self-evident idea to use the spatial light modulator for a direct modulation of the lattice wave with a corresponding

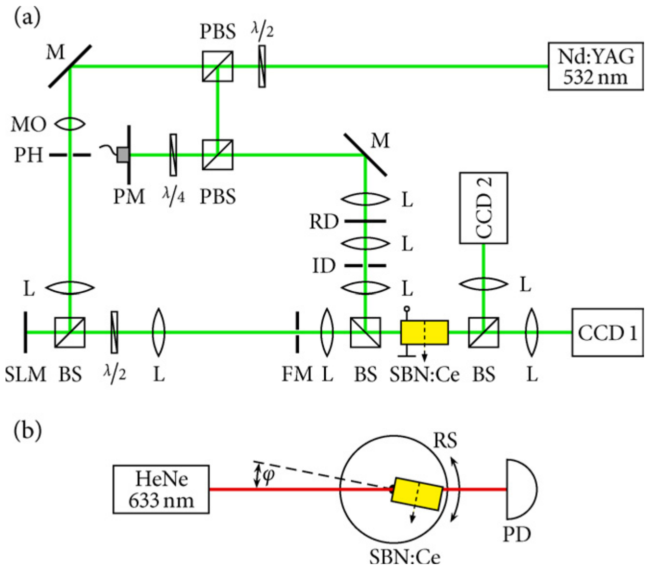

Figure 1. Experimental setup for (*a*) optical induction and Brillouin zone spectroscopy as well as (*b*) angle-dependent transmission measurement. CCD 1: near field camera, CCD 2: far field camera, FM: Fourier mask, ID: iris diaphragm, L: lens, M: mirror, MO: microscope objective, (P)BS: (polarizing) beam splitter, PD: photo diode, PH: pinhole, PM: piezo-mounted mirror, RD: rotating diffuser, RS: rotation stage, SLM: spatial light modulator.

(This figure is in colour only in the electronic version)

pattern is not successful. The reason is that lattice waves of different periodicities acquire different phase shifts during propagation and their coherent superposition therefore leads to an intensity modulation in the propagation direction due to interference. Consequently, a method of incoherent superposition is required.

Of course a simple overlay of multiple incoherent interference patterns is feasible but lacks the flexibility benefits offered by the usage of a modulator. A solution is given by the multiplexing technology known from holographic data storage. Several different approaches such as wavelength, angular and phase code multiplexing [19–21] allow the superposition of different refractive index patterns inside the volume of a photorefractive crystal and can therefore serve as a basis for the induction of multiperiodic photonic superlattices.

Compared with the commonly used sequential recording scheme, the method of incremental multiplexing [17] offers the possibility to induce the superimposed lattices with varied modulation depths by simply adjusting their relative illumination times. In fact, this enhances the flexibility of the induction process even more.

3. Experimental setup

The setup for the experimental demonstration of this new approach (figure 1) consists of two parts. The first one (figure 1(*a*)) closely resembles the setup used in [18]. A programmable spatial light modulator is used to create a phase engineered periodic wave that exhibits phase shifts of π radians between adjacent sites. Such a phase modulation enables diffraction-free propagation through the crystal and therefore allows for the induction of quasi one-dimensional as well as two-dimensional refractive index structures into a 20 mm long photorefractive $Sr_{0.60}Ba_{0.40}Nb_2O_6$ (SBN : Ce) crystal, which can be biased by an externally applied electric field of typically 1–2 kV cm^{-1}.

For the analysis of the induced lattices, Brillouin zone spectroscopy [22, 23] is performed by imaging the partially spatially incoherent output of a rotating diffuser onto the front face of the crystal and monitoring the output spectrum using a Fourier transform lens and a CCD camera.

To achieve more quantitative information about the induced refractive index structure, the transmission of a single probe beam depending on its incident angle is measured utilizing the second part of the setup (figure 1(*b*)). After the induction of the lattice, the crystal is placed on a computer-operated rotation stage and the angle-dependent transmission of the beam is measured. Since the crystal is much less sensitive in the red wavelength region, a HeNe laser at 633 nm and a very low power level (less than 1 μW) is used. This enables the analysis of the induced lattice structure while at the same time avoiding either erasure of the induced lattice or induction of additional refractive index structures by the probe beam itself.

4. One-dimensional multiperiodic lattices

We first implement our method for the induction of one-dimensional stripe patterns and analyze the induced refractive index structures in Fourier space using Brillouin zone spectroscopy as well as in real space by measuring the angle-dependent transmission as described above. Figure 2 summarizes the results obtained by Brillouin zone spectroscopy.

If only one lattice period is used during the induction process, the Brillouin zone pictures show two dark lines marking the borders of the first Brillouin zone of the corresponding lattice. This is demonstrated in figures 2(*b*) and (*d*) for lattice periods of 15 μm and 24 μm, respectively. The corresponding real space images of the lattice wave are shown in figures 2(*a*) and (*c*). The induction of a one-dimensional photonic superlattice as a superposition of these two structures is depicted in figures 2(*e*) and (*f*). The arrows in figure 2(*e*) indicate the alternating sequence of the two single periodic lattice waves. Both waves are sent onto the crystal in an alternating scheme having the same power of 35 μW for 2 s, respectively. It is important to note that this illumination time is at least one magnitude smaller than the typical dielectric relaxation time of the used crystal, which at these intensities typically is in the range of tens of seconds. The total illumination time of the induction process is about 60 s. In this case figure 2(*f*) clearly shows four dark lines corresponding to the Brillouin zone structure of the double-periodic one-dimensional superlattice induced by the superposition of the two single periodic structures.

Similar results are obtained by the measurements shown in figure 3. Utilizing the setup in figure 1(*b*), the angle-dependent linear transmission spectrum, normalized to the laser output power, is determined. For the single periodic lattices (figures 3(*a*) and (*b*)), one can clearly see two distinct

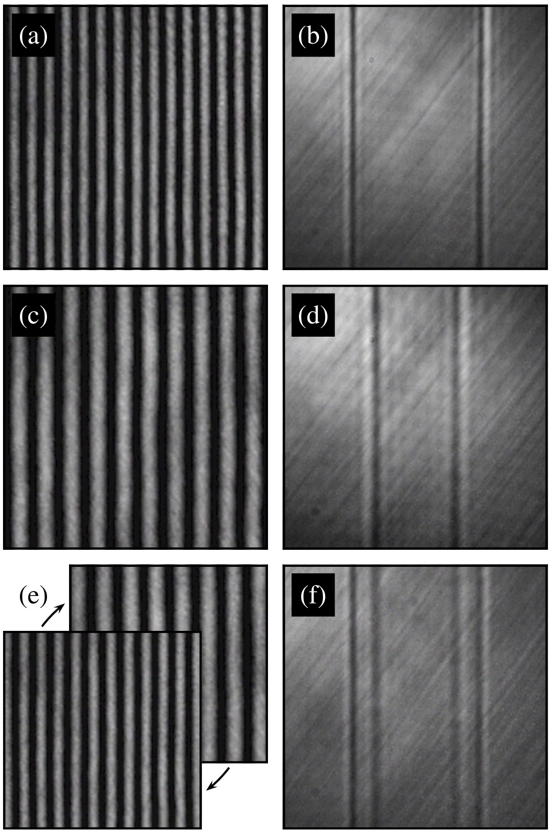

Figure 2. Lattice wave (left) and Brillouin zone spectroscopy (right) of a one-dimensional multiperiodic lattice. (*a*), (*b*) Stripe pattern with lattice period of 15 μm, (*c*), (*d*) stripe pattern with lattice period of 24 μm, (*e*), (*f*) incremental multiplexing of stripe patterns with lattice periods of 15 and 24 μm.

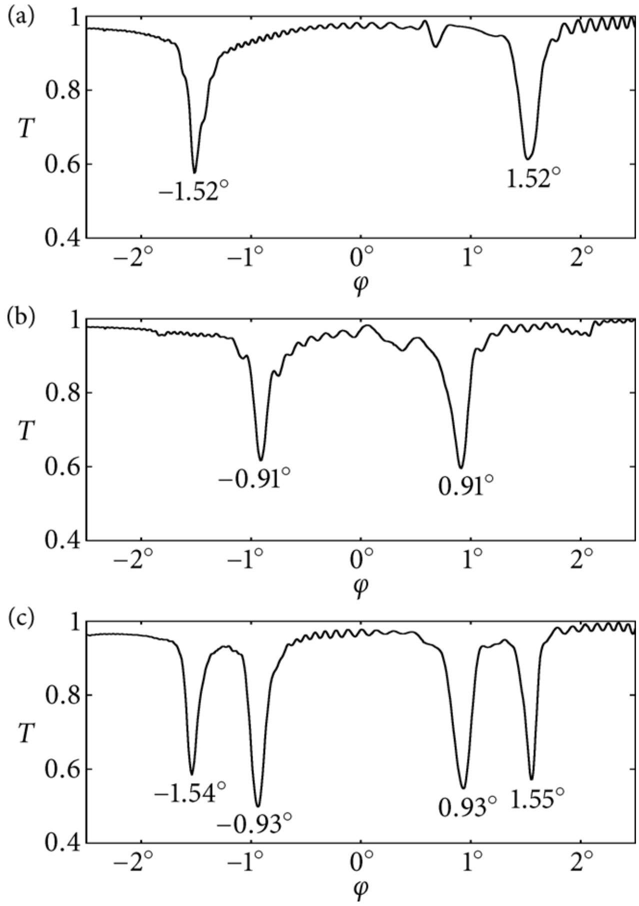

Figure 3. Normalized linear transmission T of a one-dimensional multiperiodic lattice depending on the incident angle φ (cf setup in figure 1(*b*)). (*a*) Stripe pattern with lattice period of 12 μm, (*b*) stripe pattern with lattice period of 19 μm, (*c*) incremental multiplexing of stripe patterns with lattice periods of 12 and 19 μm.

drops in the transmission spectrum due to Bragg reflections within the periodic structures. Bragg's law for the first order of these reflections is written as $2d \sin\varphi = \lambda$, where d is the lattice constant, φ is the incident angle and λ denotes the wavelength of the used probe beam. With lattice constants of $d_1 = 12\,\mu$m and $d_2 = 19\,\mu$m as well as a laser wavelength of $\lambda = 633$ nm this results in angles of $\varphi_1 = 1.51^\circ$ and $\varphi_2 = 0.95^\circ$. This is in good agreement with the experimentally measured angles as shown in figure 3. Since Bragg reflections always appear at the boundaries of the Brillouin zones, the drops in the transmission spectrum can be considered as a real space analogue of the dark lines in the Fourier space analysis shown in figures 2(*b*) and (*d*). Consequently, the transmission curve of the multiplexed superstructure (figure 3(*c*)) shows four drops which are situated at the Bragg angles of the constituent single periodic structures.

As a result, both analyzing methods clearly demonstrate the possibility to induce one-dimensional photonic superlattices in photorefractive materials by holographic multiplexing.

5. Multiperiodic lattices in two transverse dimensions

In addition to the optical induction of one-dimensional superlattices, our method can easily be extended to achieve multiperiodic structures in two transverse dimensions as well. The corresponding results are summarized in figure 4. To minimize the effect of anisotropy and thus create a truly two-dimensional refractive index structure, the so-called diamond pattern [10] is used. The used lattice waves (figures 4(*a*) and (*c*)) have a total power of 55 μW and lattice constants of 17 μm and 28 μm, respectively. As before, figures 4(*b*) and (*d*) show the first Brillouin zone of the single periodic lattices and the corresponding Brillouin zone picture of the multiplexed superstructure is depicted in figure 4(*f*). Again, the superposition of the two single periodic lattices is clearly visible by the two dark squares indicating the first Brillouin zones of the two single periodic structures.

We emphasize that the only fundamental restriction on the successively multiplexed structures is their diffraction-free propagation through the medium. Therefore, the method of holographic multiplexing may also be extended to induce more sophisticated refractive index structures, for example asymmetric lattices being a superposition of many single periodic lattices of different symmetries.

6. Conclusions

In conclusion, we have transferred the technique of multiplexing for holographic data storage to the field of

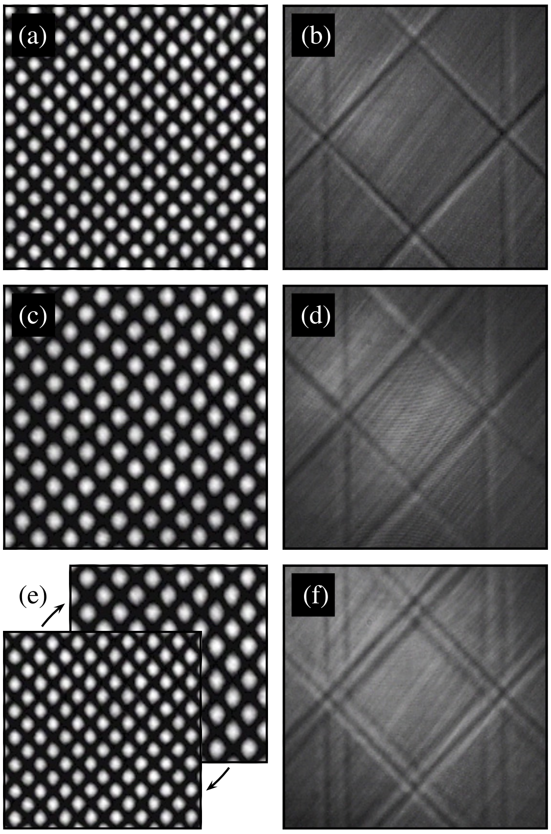

Figure 4. Lattice wave (left) and Brillouin zone spectroscopy (right) of a two-dimensional multiperiodic lattice. (*a*), (*b*) Diamond pattern with lattice period of 17 μm, (*c*), (*d*) diamond pattern with lattice period of 28 μm, (*e*), (*f*) incremental multiplexing of diamond patterns with lattice periods of 17 and 28 μm.

optically induced photonic structures. Based on known processes, we developed a modern concept of lattice induction and exemplified it for one- and two-dimensional photonic superlattices in photorefractive media. We believe that, due to its simplicity and high flexibility, the presented method can serve as a novel tool for the investigation of several fascinating effects of nonlinear wave propagation in multiperiodic photonic lattices and may also be extended to more complex and even asymmetric structures of different symmetries.

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