Light propagation in complex photonic lattices optically induced in nonlinear media

(Invited Paper)

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***Abstract*—We demonstrate the optical induction of photonic structures with different complex geometries in a nonlinear photorefractive crystal. Among the discussed lattices, there are members of all four fundamental families of nondiffracting beams. Given these complex photonic entities, we investigate their influence on linear and nonlinear light propagation.**

I. Introduction

Due to their technological importance in a multitude of application fields, artificial photonic materials have become a very active research area in recent years. In this context, nonlinear photonic structures with their unique light propagation properties originating from the interplay between nonlinearity and periodicity provide one of the most influential approaches.

In particular, the electro-optic properties of photorefractive crystals like strontium barium niobate (SBN) allow for a flexible generation of highly reconfigurable nonlinear refractive index patterns at very low power levels. The so-called optical induction technique [1] has been utilized to demonstrate, for instance, discrete solitons [2], Zener tunneling and Bloch oscillations [3], as well as discrete vortex solitons [4]–[6].

While in the past only rather simple lattice geometries were studied in these systems, currently, the interest turns towards more complex patterns. In this contribution, we present a variety of new lattice beams with different geometries, show their optical induction in a photorefractive medium, and discuss the linear and nonlinear light propagation in these fascinating photonic structures.

II. Nondiffracting Beams

Naturally, the intensity distribution of a beam used for the optical induction of two-dimensional structures should be modulated in the two transverse dimensions but has to remain invariant in the direction of propagation. Light fields fulfilling this requirement are commonly denoted as nondiffracting beams. They share the property that their transverse spatial frequency components all lie on a circle in the corresponding Fourier plane [7].

A theoretical investigation of this requirement reveals four different families of qualified field distributions. Depending on the underlying coordinate system, a distinction is drawn between discrete, Bessel, Mathieu, and Weber nondiffracting beams [7], [8].

In order to get an impression of the structural diversity that nondiffracting beams exhibit, Fig. 1 depicts numerically calculated transverse intensity and phase distributions for three members of different nondiffracting beam families.

In Figs. 1a and 1d, the structure of a first order Bessel beam is shown. While a zeroth order Bessel beam can easily be generated experimentally using an axicon [9], the experimental preparation of higher order Bessel beams is very challenging.

A member of another interesting family of nondiffracting beams is shown in Figs. 1b and 1e. Because of their unique geometry, these Mathieu nondiffracting beams can not only be utilized for the optical induction of complex photonic structures in photosensitive materials but are also outstanding patterning tools. Recently, the intensity maxima of such a Mathieu nondiffracting beam have been used for example as versatile light moulds for micro particle assemblies [10].

While Mathieu beams are described in the elliptic cylindrical coordinate system, the family of Weber beams relies on parabolic cylindrical coordinates. One example of such a nondiffracting beam with parabolic geometry is depicted in Figs. 1c and 1f, respectively.

For all four families of nondiffracting beams, we are able to transfer the numerically calculated field distributions into real nondiffracting lattice writing beams. The underlying experimental approach will be discussed in Section IV below.

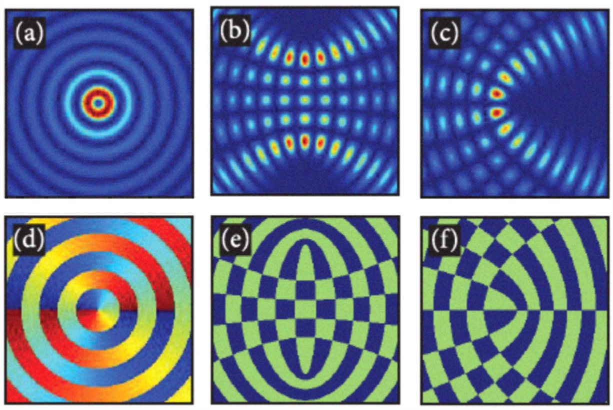

Figure 1. Transverse intensity (top) and phase (bottom) distributions for different nondiffracting beams. (a), (d) First order Bessel beam, (b), (e) fourth order Mathieu beam, (c), (f) odd Weber beam.

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III. Vortex Lattices

The family of discrete nondiffracting beams can be considered as a set of plane wave interference patterns. The classical two beam interference is a famous member of this family, showing a nondiffracting stripe pattern in its transverse intensity profile. It is well-known that besides stripes, all other regular plane tilings, i.e. square [2], hexagonal [11], and triangular patterns [12], or even quasiperiodic structures [13] can be realized with discrete nondiffracting beams as well.

However, the relative phase between the different plane waves contributing to a discrete nondiffracting beam has never been considered as a relevant parameter in these experiments. Only recently, we demonstrated for the first time that this phase relation is the key to many important lattice structures. Among others [14], we were able to create the first nondiffracting kagome lattice [15] using this new idea.

Furthermore, we developed a comprehensive framework for the description and analysis of symmetries of complex optical fields. By applying this tool set to periodic discrete nondiffracting beams, we were able to demonstrate the first construction of all three fundamental two-dimensional nondiffracting vortex lattices based on vortices of triangular, quadratic, and hexagonal shape, respectively [16]. Figure 2 gives an overview of the transverse intensity and phase structure of these fascinating patterns.

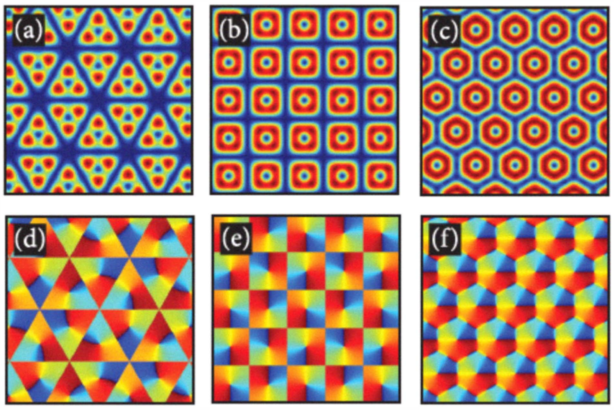

Figure 2. Intensity (top) and phase (bottom) distributions of all three fundamental periodic nondiffracting vortex lattices. (a), (d) Triangular vortex lattice, (b), (e) square vortex lattice, (c), (f) hexagonal vortex lattice.

Since optical vortices are dislocations in the phase front, they show a vanishing intensity at the disclocation point (cf. Fig. 2, top row). In addition, their rotating phase fronts (cf. Fig. 2, bottom row) lead to a twisted flow of the electromagnetic energy around these dislocations. Thus, these periodic and nondiffracting vortex lattices will find an application in many different physical fields.

IV. Experimental Realization

The setup used to generate all these complex nondiffracting beams and to utilize them for the photonic lattice induction is schematically shown in Fig. 3.

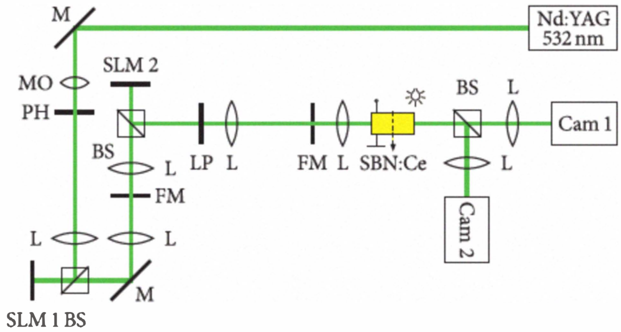

Figure 3. Experimental setup for optical induction of complex photonic lattices. BS: beam splitter, Cam 1: near field camera, Cam 2: far field camera, FM: Fourier mask, ID: iris diaphragm, L: lens, LP: linear polarizer, M: mirror, MO: microscope objective, PH: pinhole, SLM: spatial light modulator.

A beam from a frequency-doubled Nd:YAG laser at a wavelength of 532 nm illuminates a first programmable light modulator. This modulator imprints a spatial phase pattern specifically calculated for the desired lattice wave (cf. Figs. 1 and 2, bottom rows) onto the illuminating beam. Subsequently, this first modulator is imaged onto a second one which then modulates the amplitude of the beam according to the calculated intensity distribution of the lattice wave (cf. Figs. 1 and 2, top rows). The modulated beam is finally imaged at the input face of the biased SBN crystal by a high numerical aperture telescope. Within the Fourier planes of the two involved telescopes, spatial filters can be used to ensure the constraints for nondiffracting beams discussed in Section II.

The output of the crystal is analyzed with two cameras, one imaging the near field and one the far field.

V. Analysis of Optically Induced Lattices

After the described optical induction process, the actually induced structure can be analyzed by illuminating the whole crystal with a broad plane wave. The incident light is guided by the regions of higher refractive index, and, as a consequence, the modulated intensity distribution at the output of the crystal qualitatively maps the induced refractive index change [17].

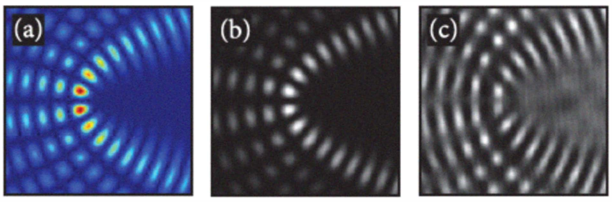

Figure 4. Optical induction and analysis of a photorefractive Weber lattice. (a) Numerically calculated intensity distribution, (b) intensity profile of the experimentally realized lattice wave, (c) waveguiding in the optically induced Weber photonic lattice.

Figure 4 summarizes the three steps for preparation and analysis of an optically induced photonic Weber lattice. First of all, the transverse profile of the nondiffracting lattice beam is numerically calculated as discussed above. Accordingly, Fig. 4a illustrates the simulated intensity distribution of the selected Weber beam. Then, the calculated profile is used as an input for our experimental setup (cf. Sect. IV), and Fig. 4b attests an excellent agreement of the actually obtained lattice writing beam to the addressed structure. Finally, the waveguiding experiment depicted in Fig. 4c clearly shows the successful optical induction of the desired photonic Weber lattice.

VI. Three-dimensional Photonic Structures and Superlattices

While all photonic structures presented so far are designed to be invariant in one distinct direction, our induction concept can easily be modified in order to introduce a modulation in this direction as well. This extends the concept of optical induction even further and allows for the creation of three-dimensional optically induced photonic lattices and quasicrystallographic structures [18]–[20].

In particular, the combination of this technique with the fundamental vortex lattices shown in Fig. 2 is interesting, since this facilitates longitudinally expanded intensity helices in periodic arrangement [16]. These unique helical intensity distributions could be utilized for the optical induction of chiral photonic structures.

Moreover, techniques known from the field of holographic data storage could be used to multiplex lattices with different feature size, thus facilitating even superperiodic structures [21].

VII. Conclusion

In conclusion, we present a novel concept of optical lattice wave generation that allows for the preparation of an unequalled variety of nondiffracting beams. For all four families of these beams, we are able to transfer calculated field distributions into real nondiffracting lattice waves. In particular, the possibility to control the relative phases of all contributing components in our setup allows us to implement fascinating new structures such as nondiffracting kagome or vortex lattices. The potential of our method is shown by preparing and utilizing these different nondiffracting beams for the optical induction of complex photonic lattices in a nonlinear photorefractive crystal.

Given these complex photonic structures, we investigate their influence on the diffraction properties of light and discuss the possibility of interesting new linear and nonlinear propagation effects. In particular, the existence of novel soliton families in these structures is an intriguing question.

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