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Direct Measurement of Photonic Band Structures by Second Harmonic Generation

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Abstract: By exploiting the phase sensitivity of second harmonic generation, we measure photonic band structures in PLLN waveguide arrays. Furthermore, we show that the concept can be applied to other photonic structures, as, e.g., photonic crystals.

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The photonic band structure of periodic dielectric media provides the basis for the design of many devices, photonic crystals are a prominent example. Usually numerical tools are used to design the photonic structure to achieve a desired functionality. However, a direct experimental characterization of the band structure of fabricated samples is not straightforward. Therefore one is often limited to the evaluation of secondary properties, like refraction or diffractive spreading of finite sized beams, to obtain valuable information about the samples. Here we propose and experimentally demonstrate a new approach which uses the phase sensitivity of second harmonic generation (SHG) in quadratically nonlinear media to measure photonic band structures directly. We believe this to be a valuable tool for the characterization of complex photonic devices.

The eigenstates of periodic dielectric media are the so-called Bloch states. In photonic bands the dispersion relation of these Bloch states relates the longitudinal to the transverse wavenumbers (diffraction relation or iso-frequency curves) as well as the frequency to the wavenumbers (usually termed bandstructure) of these Bloch states. Depending on the dielectric structure there are several bands separated by band gaps where light propagation is inhibited. Furthermore, the bands usually show a strong dispersion, i.e., dependence on the optical frequency. The evolution of linear and nonlinear optical beams is determined by the properties of the photonic bands at the spectral position of the excitation. For example, the refraction of a beam at the interface between two media is determined by the difference of the local inclination of the respective diffraction relations. Similarly the diffractive spreading inside a medium depends on the local curvature of these curves. Moreover to a large extent also nonlinear phenomena, e.g., soliton formation, modulational instability, or second harmonic generation, are determined by the interplay between the linear angular dispersion, defined by the band structure, and the nonlinear properties of the medium. In this context one has to distinguish between phenomena which rely on the local variation of the dispersion curve, for example diffraction, soliton formation, etc., and phenomena which rely on the absolute value of the wavevector, like second-harmonic generation.

Up to now some techniques have been reported to characterize the photonic band structure of periodic dielectric media [1]. However these techniques determine only the local variation of the bands, corresponding to information on derivatives. Thus, a subsequent numerical integration of the measured data is required to reconstruct the underlying wavevector dependence. By using this procedure the measurement accuracy is severely limited and the absolute value of the wavevector is not accessible because of an unknown integration constant. Therefore our goal was to implement a measurement technique which allows a direct and unconditional characterization of the band structure.

Our approach takes advantage of the following concepts: Second harmonic generation is a nonlinear process which requires matching of the wavevectors of waves at the fundamental frequency (ω_{FW}) and at its second-harmonic (ω_{SH}). Thus if one of the wavevectors is known, the other can be retrieved from the resonance condition. Furthermore, because the dielectric structure is usually only at resonance for either the FW or the SH, due to the strong dispersion of these periodic media often one of the wavevectors obeys a trivial dispersion relation. Hence we propose to use the angular dependence of the phase matching frequency to measure the absolute band structure.

Here we present an example of our technique, where we determine the band structure of a PPLN waveguide array. For this purpose we fabricated arrays of linearly coupled waveguides on 5- and 7-cm-long Z-cut lithium niobate crystals [2]. The individual guides are formed by in-diffusion of 7-µm-wide and 98-nm-thick titanium stripes for 8.5 hours at a temperature of 1060°C. Each array consists of 101 waveguides with a separation ranging from 12 to 15 µm. The resulting coupling lengths reach from 4 to 16 mm. For phase-matching SHG between the FW and the SH TM_{00} waveguide modes a QPM grating with a period of 16.751 µm was written in the sample by electric field poling. The sample could be heated in an oven up to 250°C to suppress index changes and resulting inhomogeneities of the linear coupling and the wavevector mismatch distribution due to photorefractive and pyroelectric effects. The numerically determined band structure (diffraction relation) of a typical waveguide array in our PPLN samples is shown in Fig. 1. Most importantly, the calculated fundamental bands are completely different for the FW and SH. For the FW the evanescent coupling of the guided modes in the individual waveguides leads to the formation of a cosine-shaped fundamental band which extends over a range of 4 times the coupling constant κ. In contrast, the fundamental band of the SH reduces to a single line since due to the shorter SH wavelength λ_{SH} the SH waveguide modes are strongly confined to the individual guides and hence do not overlap with each other. Consequently we have ideal conditions for applying our characterization technique, since the trivial SH band can be used as reference for measuring the FW band. The resolution of our wavevector measurement is determined by the spectral width of the SHG resonance. In Fig. 2 the SHG tuning curve for a 5-cm-long single waveguide is shown. The width of the peak is 0.3 nm (FWHM) corresponding to a spectral resolution of 1.6 mm^{-1}.

The FW waveguide modes, constituting the fundamental band, were excited with a cw laser diode HP81680 with a tunable wavelength between 1456 and 1584 nm. The input beam was elliptically shaped with 64 µm width (FWHM) and 3.5 µm height and was focused onto the polished front facet of the waveguide array. The transverse wavevector was adjusted by changing the phase-difference of the FW modes in adjacent waveguides by appropriate tilting the input beam [1]. The edge of the Brillouin zone with a phase difference of π between the modes in neighboring waveguides corresponds to a beam tilt of ~3°. For our measurement the excitation angle was scanned from -5° to +5° in small steps and for each angle the FW input wavelength was scanned from 1540 to 1550 nm. The FW and SH output from the array were separated by spectral filtering and then individually imaged on photo diodes and cameras. As a result of the measurement we obtained a direct plot of the FW fundamental band as shown in Fig. 3. The plot resembles the well known cosine-shaped diffraction curve of an array. The agreement with the calculated band structure in Fig. 1 is excellent.

Even though we demonstrated here only the measurement of the first band, the proposed method is applicable to higher order bands as well. Furthermore, in our experiments the method was modified to provide also spatial resolution of the properties of individual waveguides. An extension of the demonstrated technique should also be applicable to the characterization of the entire band structure of photonic crystals. For this purpose the crystals should be excited with a FW frequency far below the first gap such that the SH is at the frequency where the band structure needs to be measured. For such an arrangement the FW would sample the crystal structure essentially as an isotropic medium since the crystal period is too short for the FW wavelength. Hence the spherical angular dependence of the FW wavevector can be used as a reference for the measurement of the SH bands.

In conclusion we proposed a new concept for the characterization of photonic band structures in periodically modulated dielectric media with a reasonable second-order nonlinearity. We demonstrated the concept by directly measuring the fundamental band of a PPLN waveguide array at the FW wavelength around 1545 nm. The results were confirmed by comparison to our theoretical predictions. Moreover, the demonstrated concept is neither limited to the fundamental band nor is it limited to waveguide arrays. Also higher order bands or the entire band structure of photonic crystals should be measurable.

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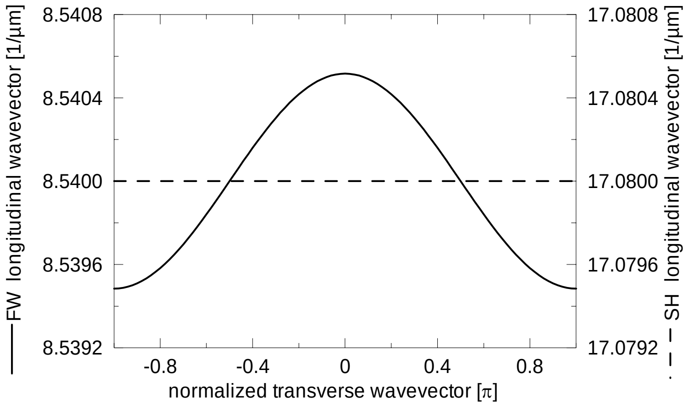

Fig. 1. Numerically determined band structure of a PPLN waveguide array (waveguide separation=13.5 µm, coupling length=6 mm).

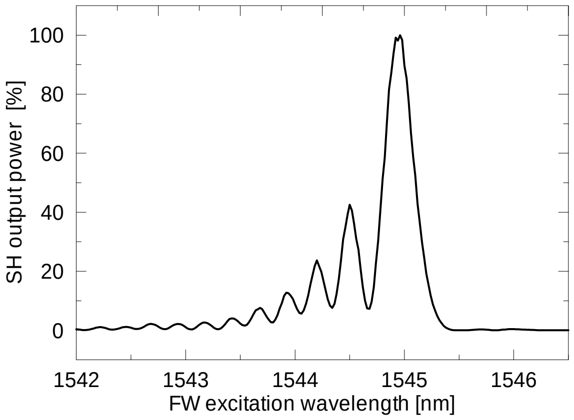

Fig. 2. Dependence of the generated SH power on the FW input wavelength in a PPLN waveguide. The width of the generated SH resonance determines the measurement accuracy of the subsequent band characterization.

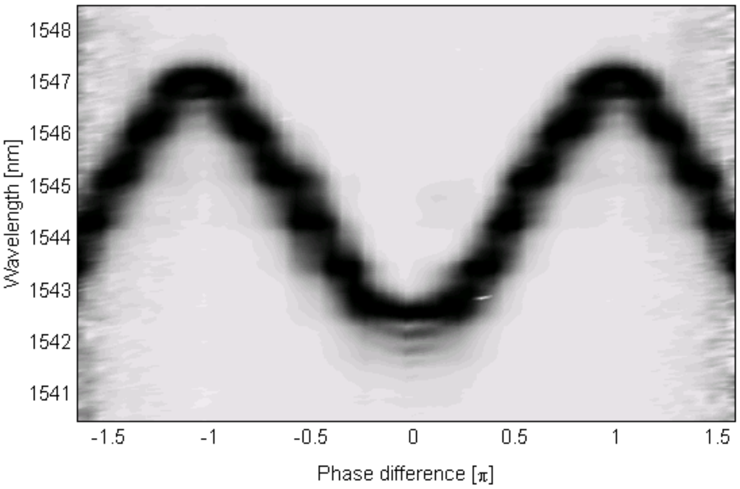

Fig. 3. Dependence of the generated SH power on the FW input wavelength and the tilt of the FW input beam in a PPLN waveguide array. This measurement reveals the cosine structure of the fundamental band at the FW frequency.