Prism coupling method to excite and analyze Floquet–Bloch modes in linear and nonlinear waveguide arrays

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We demonstrate an experimental method for the direct measurement of band structures of one-dimensional periodic optical media. With the help of a prism coupler that is used in a retroreflective scheme, the allowed bands of a waveguide array in lithium niobate are determined and the results are compared with numerical calculations. Furthermore, we demonstrate the suitability of this method to measure propagation constants of extended nonlinear modes inside the forbidden gap. © 2006 Optical Society of America

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Investigation of light propagation in periodic optical media has attracted much attention in past years.[1–3] Such optical materials with periodically varying refractive index include one- (1D) and two-dimensional (2D) waveguide arrays (WAs) of evanescently coupled channels, and three-dimensional media that may display a full photonic bandgap for large refractive index contrast. The linear modes of such structures are extended Floquet–Bloch (FB) modes, where the allowed propagation constants determine the corresponding band spectrum, which consists of allowed bands and forbidden gaps.

In the following discussion, we will focus on 1D WAs. For linear periodic media, discrete diffraction, normal and anomalous diffraction, and diffraction-free propagation of light has been observed.[2] In the nonlinear regime, defect states that are due to light-induced refractive index changes may lead to energy localization, i.e., the formation of discrete solitons.[3,4] Fabrication of nonlinear 1D WAs has been performed in various materials including polymers,[5] III/IV semiconductors,[2,3] light-induced gratings in photorefractive strontium barium niobate,[4] and arrays fabricated in $LiNbO_3$ by Ti indiffusion.[6,7]

Besides the impressive work that has been performed in the field of nonlinear light propagation in periodic media in the past,[8] only limited results have been obtained so far regarding a direct measurement of the band structure of optical samples. Excitation of linear modes of an array can be performed by endface coupling.[3,8,9] Here, to excite a pure mode of the periodic medium, the input wave form has to be matched exactly to the FB mode, which is of limited use in particular for excitation of higher modes displaying a more complicated mode structure. Furthermore, no information on the propagation constant of the excited mode is obtained. Recently, based on an earlier suggestion by Zengerle in 1987,[10] Mendelik *et al.* have presented a method for the excitation of pure FB modes, where light is coupled at a grazing angle into the lattice from a planar waveguide region.[11] Here the transverse phase-matching condition relates the grazing angle to the propagation constant of the excited mode. However, this method only proves the existence of FB modes but provides very limited information on the band structure itself, i.e., the relation of the propagation constant on the transverse wave vector.

In this Letter we present a universal experimental method for the direct measurement of linear and nonlinear band structures of 1D periodic media. With the help of a prism coupler both longitudinal and transverse wave vector components of the light entering the periodic medium can be precisely adjusted, allowing for the excitation of either pure (linear) FB modes or extended nonlinear modes.

The prism coupling method that is shown schematically in Fig. 1(a) was first proposed by Tien and Ulrich[12] for mode excitation in 1D and 2D waveguides. Since then this method has been frequently used to reconstruct refractive index profiles of planar waveguides by using the so-called mode spectroscopy.[13] In prism coupling, a high-index prism is pressed against the surface of a waveguide sample to be tested, leaving a small (air) gap between them. Light is coupled into the prism and is totally reflected at the prism base, where the angle of incidence of the light onto the prism determines the phase velocity of light parallel to the prism base. For a sufficiently small gap, the evanescent field in the gap overlaps with that of the waveguide mode to be excited. Then, optical tunneling may occur if the transverse wave vector of light inside the prism matches the propagation constant of the waveguide mode. The transverse

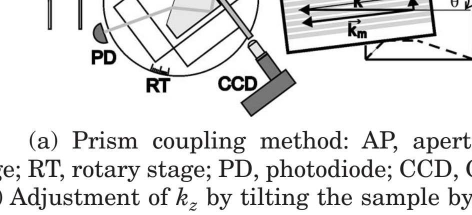

Fig. 1. (a) Prism coupling method: AP, apertures; XY, *xy*-stage; RT, rotary stage; PD, photodiode; CCD, CCD camera. (b) Adjustment of k_z by tilting the sample by an angle θ.

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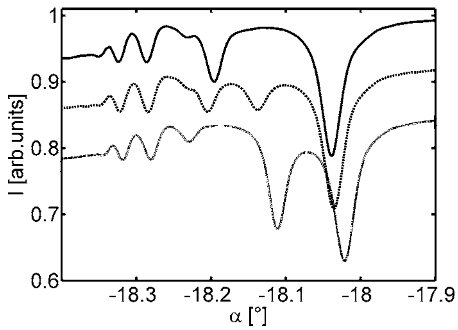

Fig. 2. Measured output light intensity I versus incident angle α for three different values of angle θ corresponding to $k_z=0$ (solid curve), $k_z=\pi/(2\Lambda)$ (dashed curve), and $k_z=\pi/\Lambda$ (dotted curve).

phase-matching condition is expressed by $n_{\mathrm{eff},m}=n_p\sin[\epsilon+\arcsin(\alpha/n_p)]$, where ϵ is the internal prism angle, n_p is the refractive index of the prism, α is the angle of incidence under which the light is coupled into the prism, and $n_{\mathrm{eff},m}$ is the effective refractive index of mode m.

The 22 mm long WA array is prepared by using an x-cut $LiNbO_3$ wafer, with the transverse z direction parallel to the c axis of the sample. First, a 8.6 nm thick Fe layer is deposited on the surface and indiffused for 22 h at 1273 K to increase the photorefractive nonlinearity. Next, a 1D array is formed by indiffusion of Ti: a 4 nm thick Ti layer is patterned to form an array with period $\Lambda=8\ \mu$m consisting of 250 stripes with a width of 5 μm. A second Ti layer with thickness 5 nm is deposited on the patterned surface. Finally, the sample is annealed for 2 h at 1273 K in air. The resulting refractive index profile is a superposition of a planar waveguide and a 1D periodic modulation.

The prism coupling setup for excitation of FB modes is depicted in Fig. 1. A rutile prism is mounted on a rotary stage with high resolution of 0.0001°. An extraordinary polarized green light beam ($\lambda=514.5$ nm) is expanded to a plane wave, passes an aperture (diameter 2 mm), and homogeneously illuminates the coupling point of the prism. In this way all 250 channels are excited with almost equal intensity. The intensity of the light leaving the prism is measured by a photodiode. The tilt angle θ of the sample that determines the transverse wave vector k_z of excited modes [Fig. 1(b)] is controlled by using a laser beam reflected on the polished sample end face. A microscope lens images this end face onto a CCD camera to study the intensity distributions of excited modes.

Figure 2 shows the measured reflected intensity I as a function of the angle α for three different tilt angles, corresponding to transverse wave vectors $k_z=0$, $k_z=\pi/2\Lambda$, and $k_z=\pi/\Lambda$, respectively. To avoid any nonlinear effects the optical power P_{in} is chosen to be below 2 nW per channel. As can be seen in Fig. 2, for $k_z=0$ (solid curve) the dip of the second band (at $\alpha\approx 18.14°$) is missing; i.e., no FB modes of band 2 are excited in the center of the first Brillouin zone. This is due to the vanishing overlap of the incident plane wave front with the (staggered) field distributions of these modes, which are orthogonal functions. A complete series of mode spectra $I(\alpha)$ for different tilt angles θ is given in Fig. 3.

From the data in Fig. 3 the corresponding effective refractive indices n_{eff} of excited FB modes are calculated. In this way the band structure of the sample is obtained (Fig. 4), which shows the allowed bands separated by forbidden regions or gaps. As can be seen, for our sample the first three bands are guided; i.e., the effective refractive index is higher than the substrate index n_{sub}.

The solid curves in Fig. 4 show the band structure as it was calculated numerically for the parameters used for waveguide fabrication. For these calculations we start with the patterned Ti stripes obtained after the lithographic process and solve the diffusion equation. From the Ti concentration $c_{\mathrm{Ti}}(x,z)$ a refractive index profile $n_{x,z}$ is obtained by using the known relation between Ti concentration and refractive index change.[14] For the profile $n_{x,z}$ we solve the wave equation by using a combination of a finite difference method and the FB approach. It is worth noting that no fit parameters have been used in numerical modeling.

To demonstrate the suitability of the described technique for the analysis of nonlinear properties, we increase the input light power and excite an extended, nonlinear (staggered) mode in the first band at the edge of the Brillouin zone at $k_z=\pi/\Lambda$, i.e., in the region of anomalous diffraction. Because of the defocusing (saturable) nonlinearity, the corresponding effective refractive index $n_{\mathrm{eff,nl}}$ decreases with time and is finally shifted inside the gap between first and second (linear) band. For an input power of $P_{\mathrm{in}}=0.25\ \mu$W per channel, the obtained value for $n_{\mathrm{eff,nl}}$ (in steady state) is shown in Fig. 4 as a solid square. As we have demonstrated recently, this mode disintegrates during propagation and becomes unstable, leading to modulation instability.[15]

For a further comparison of experimental measurement and numerical modeling, in Fig. 5 the intensity distributions of excited FB modes that are measured by imaging the polished end face of the sample onto the CCD camera are given for different bands and transverse wave vectors. As can be seen, the calculated intensity profiles are in excellent agreement with the experimental results.

In summary, we have demonstrated a new prism-based method for the direct measurement of band

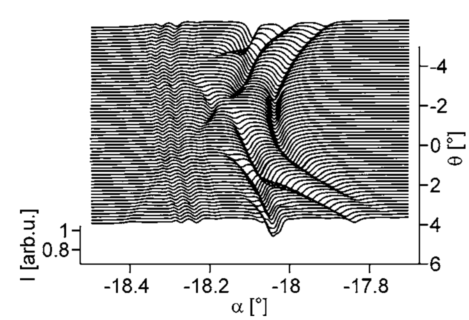

Fig. 3. Full spectrum of reflected light intensity I as a function of incident angle α and tilt angle θ.

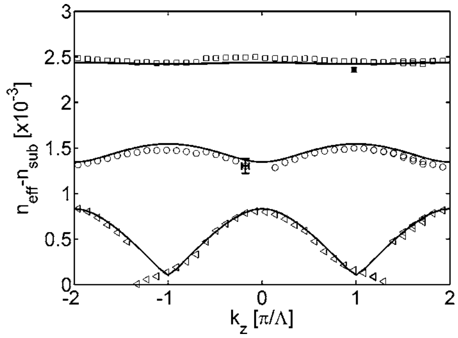

Fig. 4. Measured values (open symbols) and numerical modeling (solid curves) of the effective refractive indices n_{eff} of (linear) FB modes versus transverse wave vector k_z, relative to the substrate index n_{sub}. The solid square inside the gap is the measured effective index of an extended nonlinear mode.

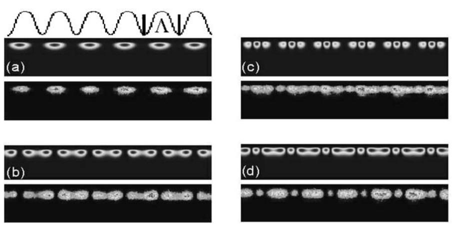

Fig. 5. Measured (lower part) and calculated (upper part) intensity distributions of extended FB modes at the output face for (a) band 1 at $k_z=\pi/\Lambda$, (b) band 2 at $k_z=\pi/\Lambda$, (c) band 3 at $k_z=\pi/\Lambda$, and (d) band 3 at $k_z=0$.

structures in one-dimensional waveguide arrays by excitation of pure Floquet–Bloch modes. The described technique can be easily expanded for the analysis of propagating (both linear and nonlinear) modes of the array by using a second prism for the outcoupling of guided light.

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