Probing the photonic band structure by resonant responsivity enhancement in QWIPs

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Abstract— **The implementation of a quantum well infrared photodetector in a planar photonic crystal yields an unpolarized detector capable to detect surface incident radiation. The in-coupling at normal incidence can be referred to a flat band region at the Γ point close to the geometrically tunable second order Bragg condition. At non-normal incidence the angular dependence of the response spectra enables to construct the photonic band structure above the light line. The measurement directly relays on the intracavity absorption of TM polarized photonic crystal modes and therefore represents a very realistic test object for intersubband devices. With this method we performed a polarization dependent band structuring mapping which showed a strong polarization mixing for the surface-plasmon waveguide used.**

***Index Terms*—Quantum Well Infrared Photodetector, Photonic Crystal, Surface Plasmon, GaAs/AlGaAs.**

I. INTRODUCTION

QUANTUM well infrared photodetectors (QWIPs) have already been extensively studied [1], including several techniques like the fabrication of one - and two dimensional (2D) gratings or random corrugations [2] that allow for detection of surface incident light. This is an import step that makes QWIPs compatible to planar processing methods and interesting for real world applications like thermal imaging or multi channel sensing. The task of a cavity that couples surface incident light to detectable TM modes can of course also be covered by a photonic crystal (PhC), which we showed recently [3]. PhCs have only been used so far in combination with a quantum dot infrared detector (QDIP) [3]. The three dimensional electron confinement in a quantum dot makes QDIPs already sensitive to surface incident light and the PhC was used mainly to increase the quantum efficiency.

In addition to the direct usability as a detector the PhC QWIP is an ideal test object for slab PhCs. By an angular resolved detection of the photocurrent it is possible measure the photonic band structure. The measurement principle is comparable to a technique presented earlier by Astratov *et. al* where resonant features in the reflection of white light from a PhC slab could be related to PhC modes [5]. In contrast to this method we use the spectral enhancement of the photocurrent of the incorporated QWIP which occurs whenever incident light couples to a PhC mode and gets detected in the QWIP region. The measurements where carried out for different polarizations of the incoming light and along different crystallographic directions of the PhC. In order to make the results adaptable also for quantum cascade lasers, the detecting region was incorporated in a typical mid infrared (MIR) surface-plasmon [6] waveguide.

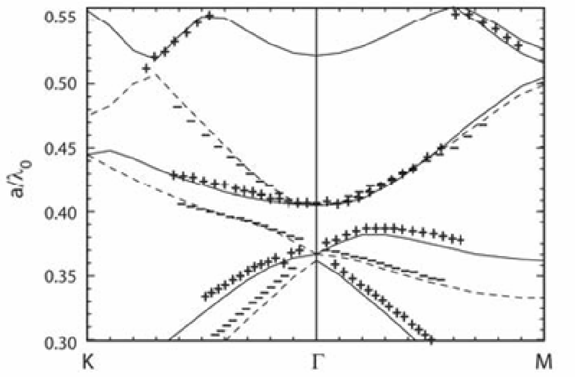

Fig. 1. A comparison of the collected data to a PWEM calculation of the 2D PhC. Solid lines refer to modes with even symmetry, whereas the dashed lines refer to modes with odd symmetry. The measured data points are marked as + if they originate from TM excitation and are marked as – for TE excitation. Note that even modes always detect purely TM polarized light while odd modes only detect TE polarized light.

II. BAND STRUCTURE MAPPING

The unpolarized light of a glow bar was directed through a Fourier-transform infrared spectrometer and either directly focused on the sample or polarization filtered in order to achieve a σ (TE) or π (TM) incident wave. By tilting the cryostat around its vertical axis the response spectra are collected at certain angles of incident. Out of the whole frequency spectrum of an incident beam only a few frequencies are coupled into the waveguide. This happens whenever a pair of frequency ω_i and in-plane wave vector $k_i^{\|}$ matches a mode of the photonic band structure. These modes

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get absorbed in the quantum wells and cause peaks in the spectral photocurrent.

The device was mounted so that either the ΓK or the ΓM direction coincided with the rotation axis. Knowing the angle θ_i and the crystallographic direction of the PhC all positions ω_i of the spectral peaks can be assigned to certain points $(k_i^{\parallel} = \omega_i/c\cdot\sin(\theta),\omega_i)$ in the reduced zone scheme and the band structure can be recorded. The measurement range is limited on the low frequency end by the air light cone and on the high frequency end by the response function of our QWIP. Fig. 1 compares the experimental data with a photonic band structure that was calculated by the plain wave expansion method (PWEM) using an effective refractive index extracted from a 1D waveguide calculation. Considering the uncertainty in determination of the air fill factor and the absence of the material dispersion in the PWEM calculation we get very good agreement with the experimental data.

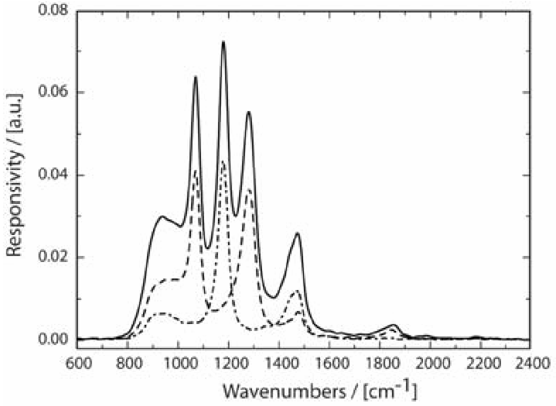

Fig. 2. Three photocurrent spectra are shown, all measured at 50° angle of incidence and along ΓK direction. They show the response on unpolarized (solid), TM polarized (dashed) and TE polarized (chain dotted) MIR broadband excitation.

III. POLARIZATION MIXING

Fig. 2 shows a typical detector response for unpolarized, TM and TE polarized light. Apart from the peak at ~ 920 cm^{-1} (which is congruent with the peak responsivity of the QWIP) there are 5 clearly displayed maxima in the spectrum taken without a polarizer. Some of the resonant peaks disappear for a TM like excitation and can only be accessed via TE polarized light. In fig. 1 all points originating from a measurement with TM polarized light are marked as a + and can be identified as even cavity modes. Even with respect to the propagation direction. This effect has partially been reported earlier for microwaves [7] and can be explained as a free space TM wave is naturally even and can therefore not couple to odd TM PhC modes. The explanation of the response for odd TM modes under TE polarization needs to include polarization conversion. This (even) TE to (odd) TM conversion is basically enabled through the PhC lattice and the vertical waveguide [8] which allows for polarization mixing as there is a sufficient overlap of the in plane electric fields of both polarizations for our surface-plasmon waveguide [3].

IV. CONCLUSION

A 2D planar PhC enables response to surface incident radiation for intersubband-based QWIPs. The peak responsivity can be identified with a flat band mode and its spectral position can be shifted via the PhC lattice constant and/or the air fill factor. The angular dependence of the spectral photocurrent was used to map the photonic band structure and to investigate polarization conversion effects. With this method a coupling of surface incident TM modes to even PhC modes and surface incident TE modes to odd PhC modes could be observed.

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