Near-Field Optical Studies of Photonic Structures

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ABSTRACT
Local optical investigations of light propagation have the advantage that the optical phenomena can be directly related to the local geometry of the photonic structure. As such, near-field optical microscopy ideally complements conventional "input-output" techniques.
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1. INTRODUCTION

Conventionally, the investigation of light propagation in advanced photonic structures, like photonic crystals, is performed with an input-output method: light is directed onto the structure and the reflected and/or transmitted light is collected. The relation between incoming and outgoing light is determined and then compared to a theoretical model. All understanding concerning the light propagation inside the structure comes from the confrontation of the experimental results with the model. While a good agreement may give a satisfying sense of understanding, a lack of agreement may leave both the experimentalist and theoretician stranded. These days photonic structures are produced in which the relation between optical properties and geometry are particularly strong, e.g. photonic crystals.[1] Small variations in geometry can result in large propagation effects.

A photon scanning tunneling microscope (PSTM) measures both the local topography of and the local distribution of light in a photonic structure.[2,3] In addition, our microscope can also map the local phase evolution of the light in the structure.[4,5] Recently, we have succeeded in tracking femtosecond pulses as they propagate through a waveguide structure.[6]

2. PHASE-SENSITIVE PHOTON SCANNING TUNNELING MICROSCOPY

In a conventional PSTM, also known as NSOM or SNOM, a small near-field optical probe is used to locally frustrate the evanescent field above a light-guiding structure. As a result the light can propagate in the probe fibre and be detected. When the probe is scanned above the structure the intensity distribution of the light inside the structure is mapped with a spatial resolution that is determined by the size of the probe. Because the height of the probe is kept at a constant height, the topography of the sample is simultaneously obtained with the optical information.[2,3]

We can measure not only the distribution of the local amplitude (not intensity!) but also the phase evolution of light as it propagates through photonic structures.[4,5] To measure the local phase evolution of the optical field inside a photonic structure, the PSTM plus structure are incorporated in one branch (signal branch) of a Mach-Zehnder type interferometric set-up. In the other branch (reference) two AO modulators shift the optical frequency of the light by 40 kHz to enable heterodyne interferometric detection. The heterodyne detection scheme enables the separation of amplitude and phase information. When the probe is scanned across the structure, both the phase evolution and the amplitude distribution inside the structure are revealed.

With both the amplitude and the phase as a function of position we can fully characterize the light propagation: a Fourier transform of the amplitude times the cosine of the phase as a function of position along the propagation direction yields all the wavevectors in the structure, Fourier filtering of the combined amplitude and phase information leads to a direct visualization of mode profiles and/or the spatial distributions of modes over the sample. Since no a priori assumptions are necessary for the analysis, the experimental results can easily be confronted with theoretical models.

3. PULSE TRACKING

Recently, we have succeeded in adding a new dimension to the measurement of local light fields in photonic structures: *time*.[6] In this case the phase-sensitive PSTM set-up is used, but now with a pulsed laser. In effect the femtosecond laser pulses are split in two: one part travels through the reference branch and the other is sent into the photonic structure and is subsequently picked up by the PSTM probe. When the reference and signal pulses are brought together, interference can only occur when the pulses arrive simultaneously at the mixing point. In effect, the amount of time overlap determines the modulation depth of the interference signal. Thus, the length of the reference branch in effect sets a reference time. For a particular reference time interference is only obtained when the pulse inside the structure is picked up by the PSTM at precisely the position that ensures that the pulse travelling the signal branch arrives at the mixing point at the same time as the reference pulse. Thus, we can determine to which position the pulse has propagated at the reference time.

The speed with which the pulse propagates, the *group velocity*, can now be unambiguously determined by measuring the position of the pulse as a function of the reference time. Since the measurement is still fully interferometric the phase information still gives the distance between the phase fronts of light inside the structure, i.e. the wavelength inside the structure. With a known optical frequency this yields the *phase velocity*.

4. CONCLUSIONS

Spatially resolved, phase-sensitive optical measurements are a powerful tool in the investigation of advanced photonic structures where the geometry plays an important role in the light propagation. The nature of the measurements allows access to the local optical properties rather than a spatially averaged quantity, for example the average refractive index. Also, the local measurements of, for example, the group velocity do not suffer from integrating all propagation effects through the entire structure. Combining amplitude and phase-sensitive or time-dependent PSTM measurements, allows a direct determination of mode profiles, losses, reflectivities, etc.

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