Waveguide Group Velocity Determination by Spectral Interference Measurements in Near-Field Optical Scanning Microscopy.

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Abstract: Measurement of spectral interference with a near-field scanning optical microscope is used to determine directly the variation of group velocity between modes of a planar slab waveguide as the modes propagate along the guide.

OCIS codes: (180.5810) Scanning microscopy; (320.0320) Ultrafast optics; (230.7370) Waveguides

Near-field scanning microscopy (NSOM) can be used to probe the optical fields inside planar optical waveguides. The advantage of NSOM is that although the properties of ideal waveguide systems can be modelled, NSOM can give real data to show how the devices perform in the presence of imperfection, or in cases where modelling is difficult and not well-understood. NSOM has been applied to waveguide systems from simple Y-junction couplers [1] to complex photonic crystal waveguides [2]. For ultrafast pulses, NSOM, combined with modulation techniques, has been used to image pulses propagating in rib waveguides [3], and recently in photonic crystal waveguides [4]. Measurement of propagation in this way can provide information about the group velocity within the guide, by measuring directly how the pulse envelope moves as a function of time. However, these measurements are complex and time-consuming, as the pulse must be carefully tracked as it propagates down a considerable length of guide.

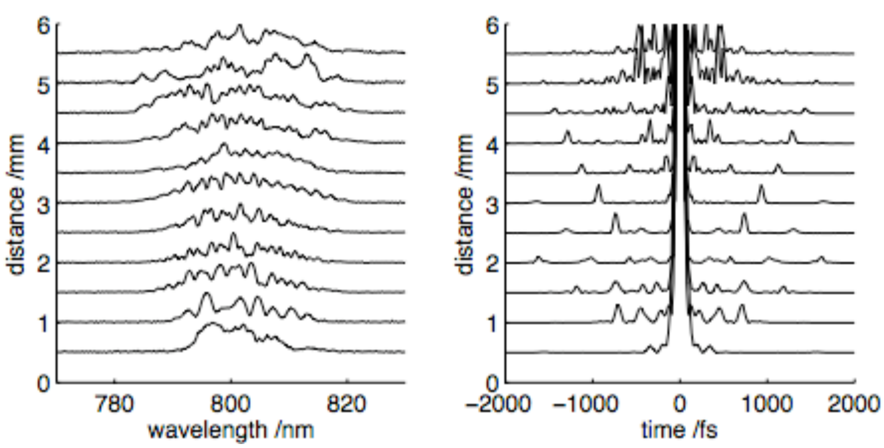

Figure 1: (left) Spectral beating caused by pulse–pulse time separation as pulses propagate in different modes of a slab waveguide, measured using the NSOM, and (right) Fourier transform of spectral beats, directly showing increase in time separation between pulses propagating in different modes as they travel along the waveguide

In this paper we demonstrate a simple way to measure group velocity differences between different modes in a planar guide, using the broad spectrum of the femtosecond pulse to advantage. In a multimode guide, a launched pulse may couple into in several different modes, which will propagate at different group velocities. As the pulses travel down the guide, they will separate in time. An NSOM probe at some point along the guide can pick up the field from all the different modes, and once these fields are superposed, different spectral components can interfere to produce modulation across the spectrum in the same way that can be seen from the output of, for example, a Michelson interferometer [5]. The time spacing of the pulses can be related directly to the period of the fringe modulation across the spectrum. The fringes are only observable if the probe is sufficiently local, as the spectral position of each fringe varies rapidly with distance along the guide.

The experiment uses Ta_2O_5 slab guides on an SiO_2 substrate. The slab is 500nm thick, and guides of 3-5 μm width have been used. These guides can support up to ~20 modes. The 100fs pulse from a Ti:sapphire laser is coupled into the guide, and the evanescent field is sampled using an uncoated fiber tip with dimension ~100nm, which is locked to within 20nm of the guide surface. The output of the fiber is sent to a CCD-based spectrometer.

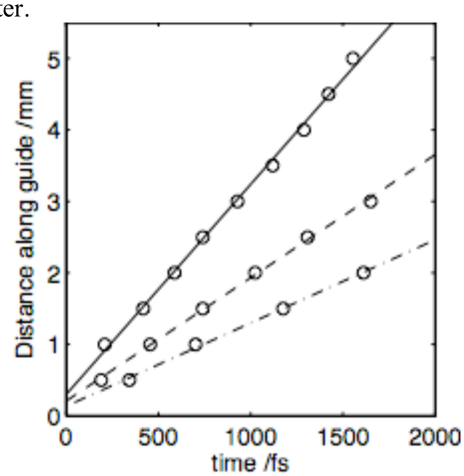

Figure 2: time separation as a function of distance down guide for three different pairs of modes

Figure 1 shows the spectra at different positions down the guide. Modulation can clearly be seen which varies with distance. The Fourier transform of the spectral intensity is shown in the right-hand graph of fig. 1. The modulations in frequency produce peaks in time, which represent the time separation between pairs of modes. As can be seen from the figure, these show clear linear increase with distance. Figure 2 shows the splitting increase versus distance for three different pairs of modes. The time separations can be converted directly into group index differences between modes. The three data sets shown correspond to modes with group index differences of 0.105, 0.174, and 0.258.

Modelling of the guides using effective index and finite element techniques can be used to calculate group indices if the exact values of the material dispersion are known. The material dispersion of Ta_2O_5 is variable dependent on the exact deposition technique, and annealing details [6]. Modelling using both effective index and finite difference techniques has been carried out, and while detailed behavior of the modes depends on the exact material dispersion, the form of the group index variation is consistent with our measured data.

The mode differences are sensitive to the intensities in different modes of the guides. Variations in the mode differences seen can be produced by changing the coupling geometry, and could be used to monitor the distribution of intensity between different modes within the guide. In addition, because the NSOM can be used to scan across and along the guide with sub-100nm precision, the spectral profile across the guide can be gathered, and integrated to provide detail of the mode cross-sections, and information about mode coupling and attenuation as a function of distance down the guide. Measurements on few-mode guides are in progress to provide a simpler system to interpret, but the initial experiments indicate that this is a sensitive technique for probing the modal properties of planar waveguides with ultrafast laser pulses.

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