Temporally Shaping Pulses with a Metamagnetic Metamaterial

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Abstract

Coherent excitation in optical spectroscopy and photo-induced processes like second harmonic generation depend on temporal properties of ultrafast pulses. In this work, we demonstrate that metamaterials can be fabricated to have very large spectral dispersion properties that can positively affect both the temporal envelope an ultrafast pulse and the phase of each spectral component.

1. Introduction

The control of broadband optical pulses has risen over the last few decades to enable optical waveform generation [1], i.e. the design of arbitrary pulse profiles at optical frequencies. This has led to a rapid development of characterization techniques that employ broadband pulses [2,3,4] and can at times operate as single pulse measurement techniques for complex systems [5,6]. Essential to the control of optical pulse profiles is the introduction of arbitrary dispersion into the optical train, typically accomplished by spatially separating and addressing individual frequency channels and can be done transmissively with acousto-optic modulators. Structured systems offer the possibility of wavelength dependent, engineered dispersion [7]. In this work we explore the use of a resonant metamaterial as a dispersive element for optical pulse shaping. We directly measure the spectral group delay dispersion (GDD), which is the material property responsible for changes in pulse shape. In the example system, we demonstrate that pulse profile characteristics used in shaped pulse experiments can be generated by metamaterial systems.

A light pulse interacting with a metamaterial can be treated linearly as a filter with a spectral transfer function. For all but the shortest pulses it is useful to expand the phase of the transfer function in a Taylor series about some reference "carrier" frequency [8]. Individual orders in the expansion have very specific effects which can be discussed separately in terms of their effect on the pulse's time-domain intensity envelope. The second-order phase derivative, called group delay dispersion (GDD), is the leading order (and usually dominant) term responsible for changes in the shape of a propagating pulse when it passes through a dispersive optical system.

2. Metamagnetic Material with Spectral Dispersion

In this work, we examined a magnetic grating, sometimes called a metamagnetic metamaterial, made up of lines composed of vertically paired metal strips with dielectric spacing layers [9]. The schematic and SEM image for such a grating are shown in Fig. 1. When using normally incident transverse magnetic (TM) polarized light, the magnetic field of the incident plane wave is aligned parallel to the long metal strips separated vertically by a distance that results in a magnetic resonance near 800 nm. The electric field couples into the periodic silver lines with a resonance near 525 nm, which is slightly less than twice the period of the grating structure.

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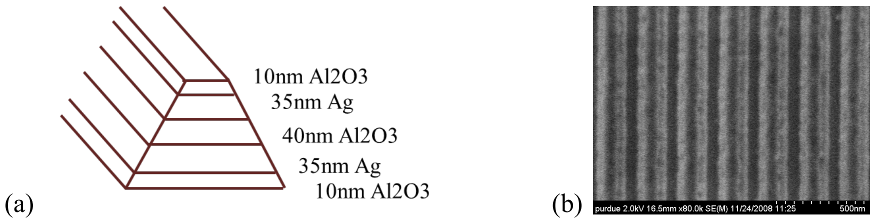

Fig. 1: a) Schematic for a magnetic grating with materials and thicknesses as given; the period was approximately 300 nm. b) SEM of a grating similar to the one used.

Using spatial harmonic analysis (SHA) [10], the complex refractive index can be determined from the s-parameters of the metamaterial simulation. The real part of the refractive index and the GDD, which is given by:

$$\mathrm{GDD} = \frac{\partial^2 \phi}{\partial \omega^2} = \frac{L}{c}\left(\frac{\partial^2 n}{\partial \omega^2}\omega + 2\frac{\partial n}{\partial \omega}\right), \tag{1}$$

are shown in Fig. 2 (a). Two sharp index changes due to the resonances in the material near 400 and 800 nm are evident in the upper plot. Near these resonances the spectral dispersion of the material changes quickly and this results in large values for the GDD as shown in the lower plot of Fig. 2 (a).

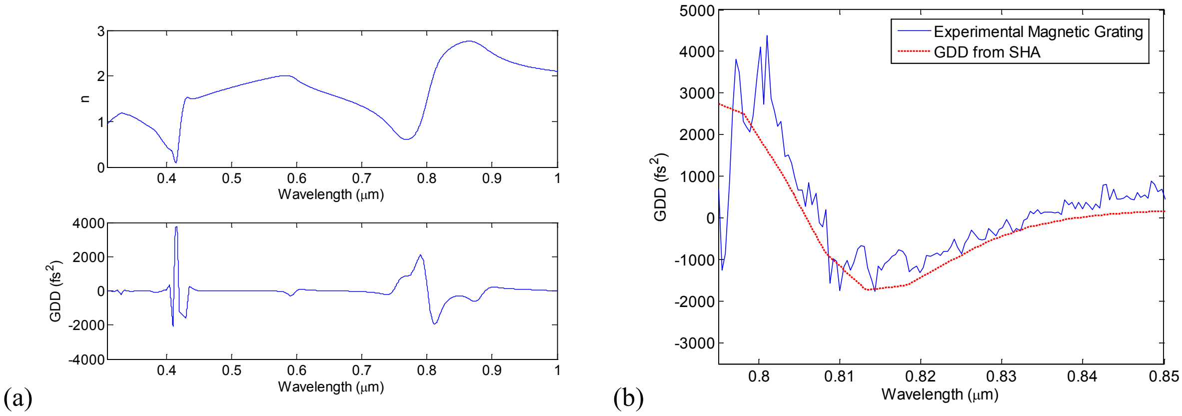

Fig. 2: a) Refractive index (upper plot) and GDD (lower plot) for the magnetic grating calculated using SHA. b) MIIPS measured GDD of a magnetic grating (blue solid line) and simulated GDD (red dashed line).

To experimentally measure the GDD of a metamagnetic material, we used the MIIPS technique [11,12] with an ultrafast oscillator, the Griffin-5, from KMLabs. The oscillator had a 100 nm full-width-half-max (FWHM) bandwidth quasi-square profile capable of transform limited pulses below 15 fs in duration. The measured dispersion from a magnetic grating is shown in Fig. 3 (b) (solid blue line) and is compared with the GDD derived from the refractive index found using SHA (dashed red line). Very good agreement can be seen between the measured dispersion and simulation. One can also observe that the dispersion lies between about 3000 fs^2 and -2000 fs^2 and crosses zero near 808 nm, which was near the center of our oscillator bandwidth.

Looking again at the refractive index in Fig. 2 (a), the change in index near 800 nm corresponds to approximately a π phase step. The effect of a phase step on the temporal shape of a 10 fs pulse (95.3 nm Gaussian FWHM spectrum) that has a similar bandwidth to our experimental ultrafast pulse can be seen through MATLAB simulations of an ideal π phase step (Fig. 3 (a), blue output), a phase step close to the experimental dispersion (Fig. 3 (a), red output), and the dispersion calculated from the refractive index calculated using SHA (Fig. 3 (b)). The center wavelength of the pulse was placed at the inflection point at the center of the phase step. Some broadening is observed due to non-zero dispersion over a large bandwidth that is related to how sharp the phase step transition is. More interestingly, there is a strong dip in the center of the temporal field intensity profile of the pulse. This is due to the fact that the dispersion is anti-symmetric across the laser bandwidth.

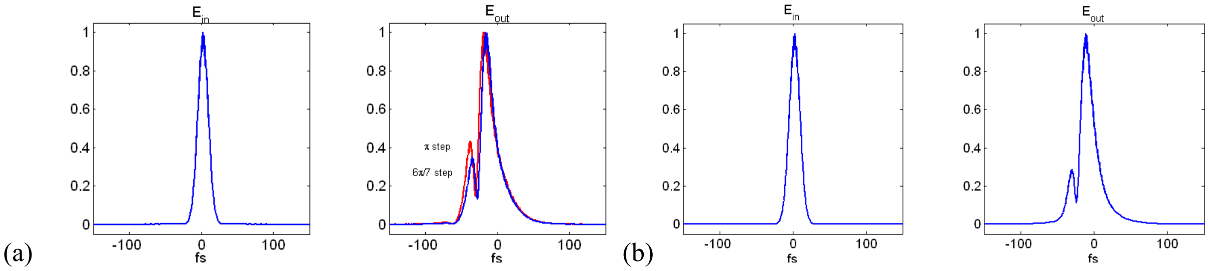

Fig. 3: a) Simulation of the effect on a 10 fs ultrafast pulse due to a step phase centered at 800 nm with a step change of 6π/7 (blue) and π (red). b) Simulation of the effect that a metamagnetic material with 130 nm physical thickness has on a 10 fs pulse. The envelopes of the input and output field amplitudes are shown in the left and right panels, respectively.

3. Conclusion

In conclusion, GDD values of metamaterials with strong resonances, such as the magnetic resonance explored here, can create changes in the effective refractive index that are an order of magnitude larger than a dispersive glass several orders of magnitude thicker. Possible applications of dispersive metamaterials include pulse shaping and compression with thin film filters of less than a micron of thickness. In the future, more carefully designed metamaterials should yield thin and precise temporal pulse shape control. Such highly tailored profiles could potentially be useful in ultrafast systems, integrated nanophotonics, and coherent control. By controlling the GDD in a metamaterial, it could be possible to compress or stretch ultrafast laser pulses with only nanometers to microns of material thickness rather than the millimeters to centimeters of glass or path length used in a typical ultrafast laser compressor. Future efforts will explore more advanced designs of metamaterials and perform GDD measurements over a broader bandwidth of laser wavelengths to look at the effects of dispersion on even shorter pulses.

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