Observation of nonlinear phenomena with a 1550nm femtosecond pulsed laser in a fiber optic

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Abstract

Modern telecommunications are getting to a limiting point given by the speed of electronics. Rather than using electrons, photonic chips use light as an information-carrying medium. Using light brings many benefits, like reducing heating (photons are massless), increasing information speed, and spending less power. Of the greatest potential in photonics is the use of nonlinear optical phenomena, though the measurement and characterization of such properties in guided structures are challenging.

In our experiment, a 1550 nm femtosecond pulsed laser is coupled from free space into a fiber optic cable and its spectral response is characterized by using an optical spectrum analyzer (OSA). Through controlling the intensity of the beam in a specific bandwidth (~1550-1585 nm), nonlinear effects are observed and quantified. Due to the material of the fiber, the temporal regime and the repetition rate of the laser, we can attribute those nonlinear changes to a Kerr effect, in particular, spectral broadening caused by self-phase modulation. Finally, we treat the data obtained with the OSA with a MATLAB code to create a superior graphical representation of nonlinear phenomena in the guided structure and quantify some output pulse characteristics.

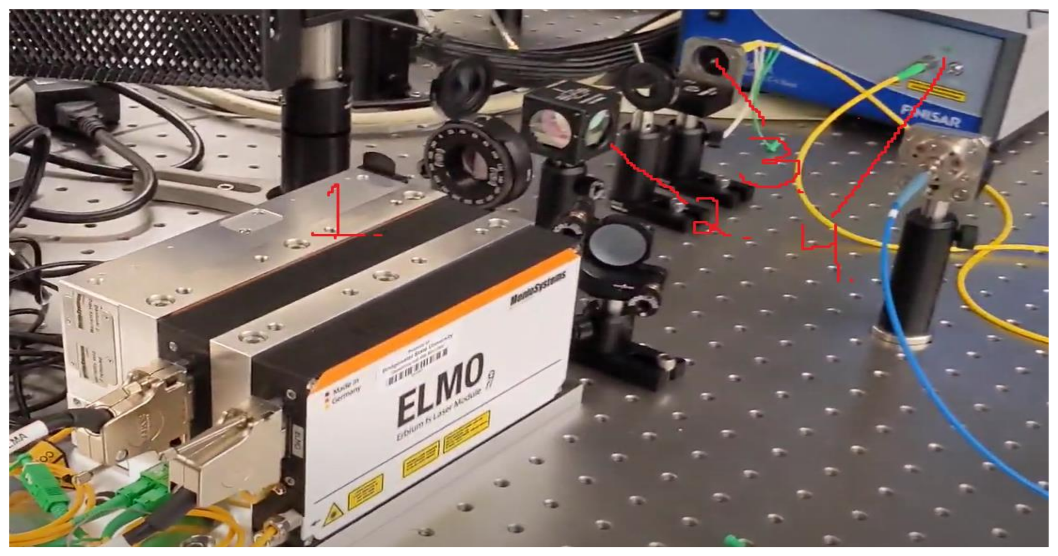

Figure 1. Setup of experiment: 1. is the laser, 2 the polarizing beam-splitter, 3. The optical fiber input, and 4. the Waveshaper.

Introduction

Nonlinear Optics is a branch of optics devoted, in brief, to the study of how an incident light of sufficient intensity produces nonlinear responses (e.g., higher order effects from the electric field) about the incident light's properties (such as the phase and frequency) and the material itself (given sufficient nonlinear susceptibility of the material), rather than predictable, linear responses. Though nonlinear optical effects may have been observed earlier, the field's nascence begin in 1961 when Peter Franken et. al demonstrated second harmonic generation by focusing a pulsed ruby optical maser (electromagnetic waves in the microwave wavelength are used rather than visible light, as in lasers, in a maser) into crystalline quartz. Today, the nonlinear effects of light-matter interactions are utilized in areas such as medicine and telecommunications.

The optical Kerr Effect calls for a change in the refractive index of a material in proportion to the intensity of a light beam, given as: $n = n_0 + n_2 I$, where n_2 represents the nonlinear refractive index, given as: $\frac{3}{4n_0^2\varepsilon_0 c}\mathrm{Re}\{\chi^3\}$ with χ^3 being a fourth-rank tensor with 81 elements known as the third order nonlinear susceptibility.

The Kerr Effect gives rise to an important phenomena known as self-phase modulation, whereby a self-induced phase shift can be given as: $\phi_{NL}(z,t) = \frac{2\pi}{\lambda} n_2 I(t)Z$, where z represents the distance travelled by the wave. A symmetrical broadening of the pulsed wave is noted: though the overall shape of the wave packet remains the same, the individual wavelengths (and consequently frequencies) are separated. A positive nonlinear refractive index would shift the front of the pulse towards lower frequencies (red shift) and the back of the pulse towards higher frequencies (blue shift), while a negative nonlinear refractive index would yield the opposite.

Figure 2. *Input* pulse of the laser centered about 1570 nm with -30 dBm as a reference level (from the OSA).

Methods and Materials

Prior to any laser use, proper safety precautions are taken to prevent injury; Thorlabs LG11 Safety Glasses specified for near infrared wavelength of **1550 nm with Optical Densities (OD) of 7+ (10^7 attenuation rate) are required for the laser with 60 kW peak power and 500 mW average power t**o attenuate below the max permissible exposure according to the MIT Laser Guide (see the right-side figure); scattering and diffuse materials present should be considered and appropriately placed; notification for incoming outsiders of the lasers status should be displayed; flammable and chemically hazardous material should be considered and appropriately placed.

Proceeding safety precautions, a **Menlo** femtosecond pulsed laser emitting in free space and at a wavelength around 1550 nm, essential in telecommunications, is turned on via computer software (ELMO) and amplified with the same software (ELMA). The laser's blocking slit can be moved up, and the exposed laser is then guided via a set of irises (for alignment), polarizer managing devices (a Half Wave Plate, that rotates the linear polarization of the light), and a polarizing beam-splitter, which splits the light into reflected and transmitted light. The transmitted light is coupled into a fiber and first sent into the OSA Optical Spectrum Analyzer Yokogawa AQ6730D OSA, with an average power of around 20 mW.

Once an initial characterization of the wave spectrum is completed on the OSA, further adjustments are made through a waveshaper Finisar (Fig. 1), this device allows us to control the amplitude and phase of the different components in the pulse. For our study, a square-like pulse shape is selected, and the wave spectrum is set to be centered around 1565 nm with a range of 40 nm (1545 – 1585 nm) as a function of power output on the vertical axis centered about -30 dBm. We had successfully mounted and aligned the set up and obtained NL effects in the optical fiber. In a second stage of the intership, we have used LabView software and GPIB protocols to connect the different devices to obtain the data directly into the computer. The driver's management was challenging, and we are still working on getting the proper cables for communication. This data collection issue did not affect the observation of the effect of dispersion in the NL phenomena, making the fiber act as a time-lens. For pedagogical purposes we display here the results from Professor Serna's Ph.D thesis, which follows the same trends and shapes of our set-up.

Results

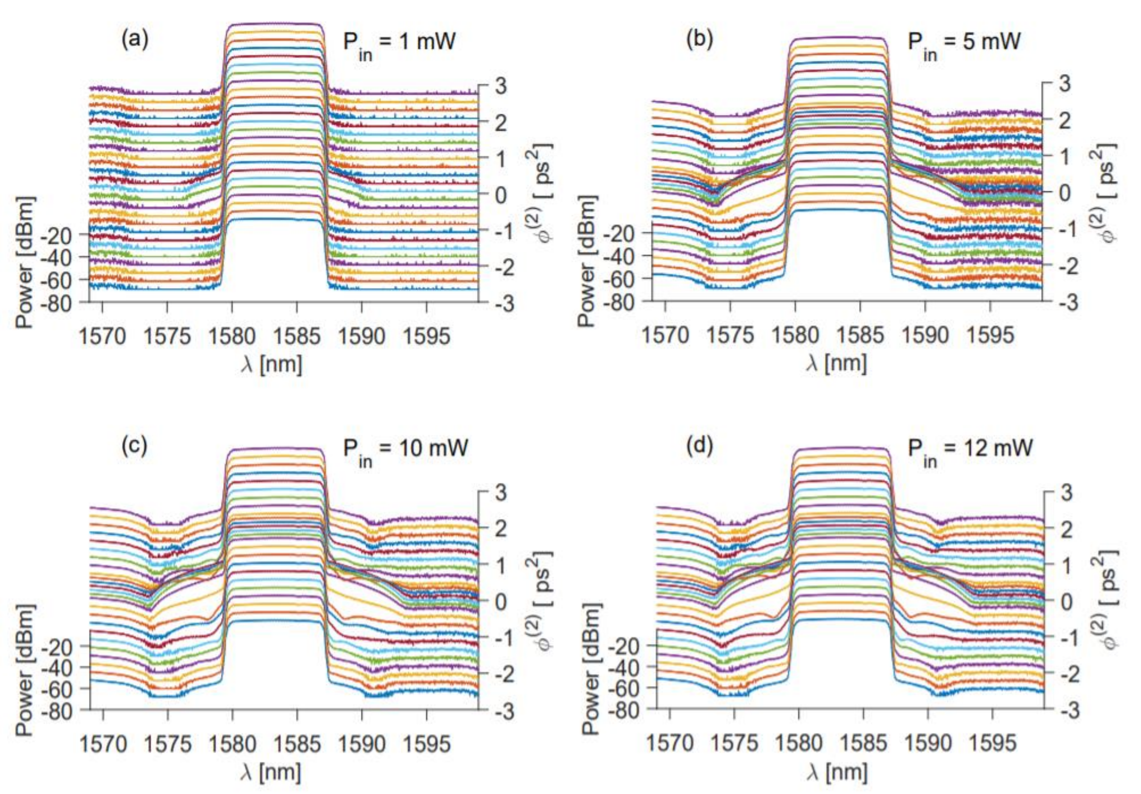

Figure 2.25: Output spectra of a two meters fiber at variable dispersion for different average input powers: (a) 1 mW, (b) 5 mW, (c) 10 mW and (d) 12 mW.

Figure 3. Depiction of various output spectra from Dr. Serna's PhD thesis, which we attempted to replicate.

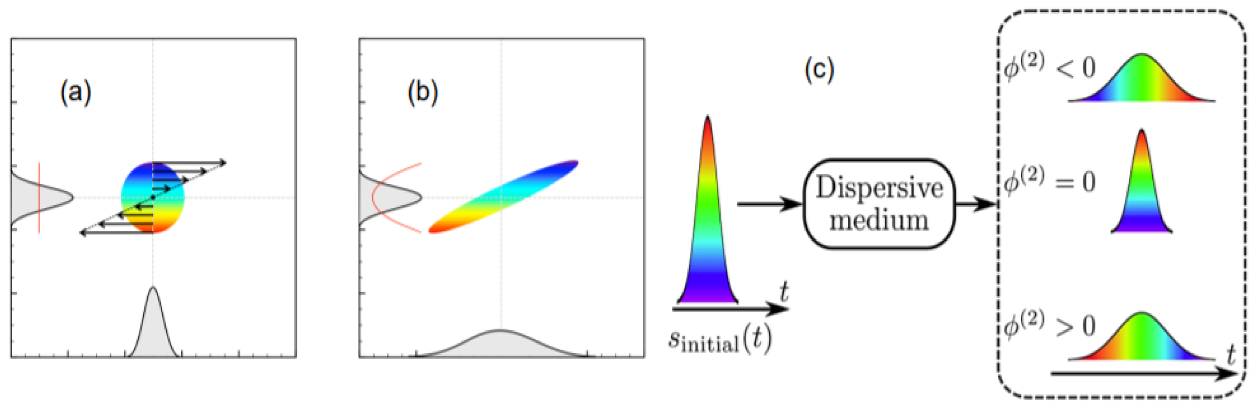

Figure 2.3: Schematics of a pulse stretching. (a) Fourier limited pulse. (b) Stretched pulse with a positive introduced dispersion ($\phi^{(2)}>0$), the red components are sent to the front of the pulse increasing its duration and changing the phase relation but leaving the spectral shape unaffected. (c) Different sign effect in the pulse duration and the relative position of the different frequencies after the dispersive effect[93].

Figure 4. Unchirped vs. Chirped pulses after a pulse travels through a positive introduced dispersion (top) or negative introduced dispersion(bottom); time = horizontal axis, vertical axis = frequency.

Graph

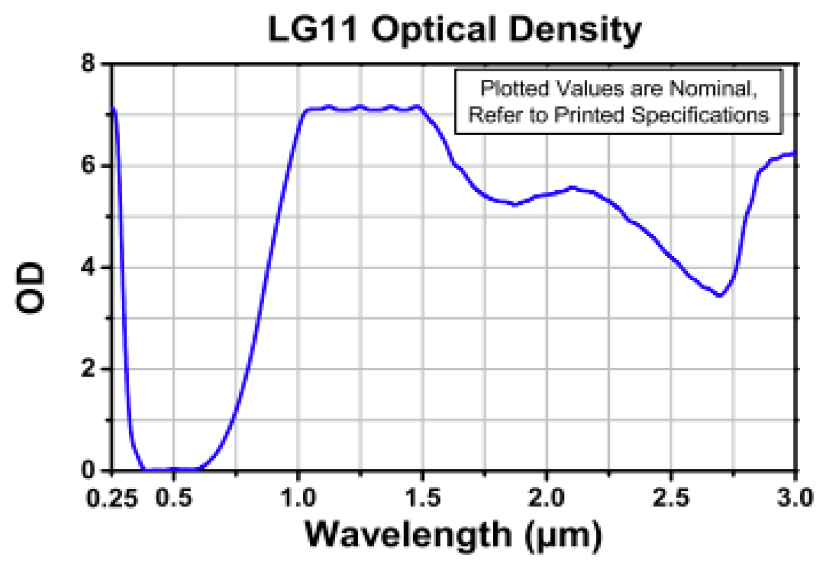

Figure 2. A graph showing the required ODs for various wavelengths taken from Thorlabs website – see 7+ for 1550 nm, the wavelength of the laser used in our research (https://www.thorlabs.com/drawings/5c53f63a7d013ead-48E3A21F-CA09-C68E-F2E85DEF3C7BE36D/LG11-SpecSheet.pdf).

Discussion

The spectrum in the "Results" section depicts a square-like input pulse of similar wavelength (1583 nm) with an input power of 1mW, 5 mW, 10 mW, and 12 mW measured at the output of a two-meter long fiber as a function of the introduced dispersion. The spectrum was originally collected with an Ando AQ66317 OSA with a resolution of 0.5 nm (equal to our experiment) over a span of 30 nm (vs. 40 nm for our experiment) with a total of 1001 points (the inability to get as many points as in Dr. Serna's thesis was an issue when using LabVIEW): the data was then compiled in MATLAB and the spectrum shown was generated.

The spectral broadening of the pulse is noticeable, especially near zero dispersion, as can be seen in the image. This is because the pulse at zero dispersion is shortest as can be seen in Figure 4 (c). With pulses there is a Fourier relation in time and frequency/wavelength band which mandates a shorter pulse in the time-domain yield a larger frequency spread, in the other sense, and for our case, cutting the spectrum from Figure 1 into only sub-10 nm span increases the pulse duration, we estimated this to be in the order of few picoseconds. As seen, other input powers of 1 mW, 5 mW, and 10 mW were used in Dr. Serna's thesis, though, as expected, the nonlinear effects were not as pronounced with these lower intensities. One can quantify the spectral broadening for the varying powers: the curvature should, moreover, depict a positive Kerr Material, as would be expected from silica from the optical fibers.

Conclusions

We have successfully demonstrated guiding a 1550 nm femtosecond pulse laser coupled from free space into a fiber optical cable and characterized the spectrum in the OSA. We have observed for the first time at BSU a non-linear third order optical effect attributed to SPM spectrum broadening. Data acquisition with LabView was challenging. Alternatively, Dr. Serna's Ph.D thesis data compiled in MATLAB, as the process and specifications were similar, was used to show the intended non-linear effects.

For the future, greater familiarity with Python and MATLAB would be helpful with data acquisition and data analysis. Also, Fourier transforms will be used to trace back from the frequency spectrum the input and output pulses in the time-domain: this could enable a clearer view of the spectral-broadening and resulting frequency spreads as well as optimize nonlinear materials for all-optical applications.

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