Dispersion compensation in mode-locked thulium/holmium doped fiber laser

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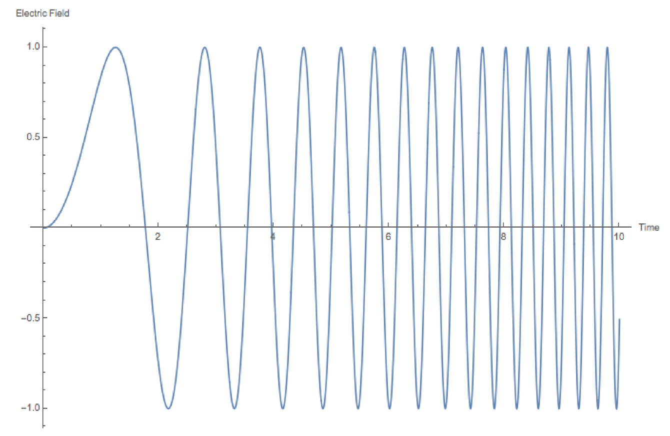
Motivation

We are using an all-fiber laser with thulium/holmium doped gain fiber. When mode-locked, the light inside this laser travels in pulses. Our goal is to get these pulses as short in duration as possible. However, due to dispersive effects caused by the fiber, the light experiences group velocity dispersion and third order dispersion, which distorts and lengthens the pulses. Both types of dispersion can be managed by using several varieties of fiber whose dispersive components cancel each other. We will try a type of ultra-high numerical aperture fiber called UHNA-7 to compensate for both.

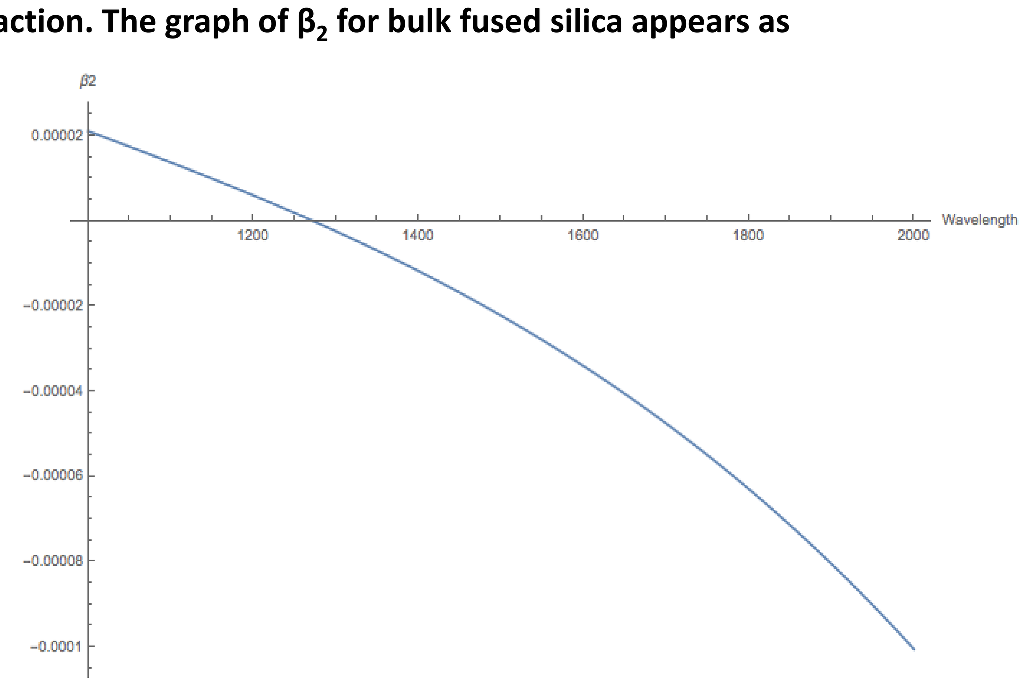
Group Velocity and Third Order Dispersion

Group velocity dispersion is a change in the velocity of spectral components of a wave pulse with respect to the carrier frequency. Specifically, different spectral components of the pulse reach a given point at different times, causing the pulse to distort in what is called "chirping". A simplified example of chirping can be seen below:



Because of this separation of spectral components, the pulse becomes longer in duration than it was initially. The goal is to create shorter and shorter pulses of light, which means we need to find a way to compensate for this dispersion.

The parameter which determines group velocity dispersion is β_2, which is related to the second derivative of the Sellmeier equation for index of refraction. The graph of β_2 for bulk fused silica appears as



although the graph shifts to the right inside optical fiber. As is seen here, β_2 can be either positive or negative.

Third-order dispersion is the rate of change of group velocity dispersion with respect to frequency; i.e. β_3 is the derivative of β_2.

Net Cavity Dispersion

The thulium/holmium doped fiber that we are using in our laser cavity has a positive β_2, while the standard single-mode fiber that makes up the rest of the cavity has a negative β_2. Net dispersion in the laser cavity is found by adding the products of the β_2 value of a fiber and that fiber's length. The net cavity dispersion for our current setup, with only these two types of fiber, is

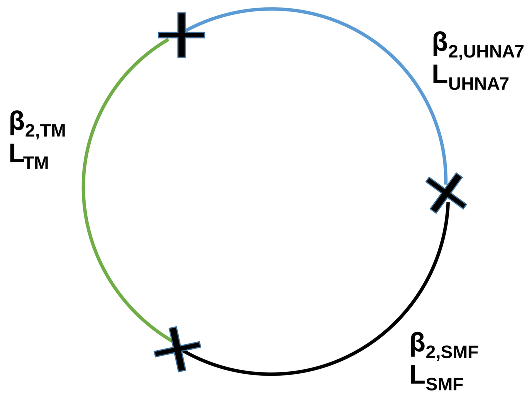
$$\beta_{2,TM} L_{TM} + \beta_{2,SMF} L_{SMF} = \left(0.01\ ps^2/m\right)(1.24\ m) + \left(-0.085\ ps^2/m\right)(4.46\ m) = -0.366\ ps^2$$

Finding a third fiber with a positive β_2 value that will compensate for this dispersion is difficult. At 2μm light, where our laser operates, most β_2 values are highly negative. Some fibers with an ultra-high numerical aperture, however, have a positive β_2. We have chosen a fiber of this type, called UHNA-7 and having a β_2 value of $0.13 ps^2/m$, to add to our laser.

When group velocity dispersion is near zero, then third-order dispersion dominates, so we need to compensate for that as well. Luckily, UHNA-7 fiber has a β_3 value which is also opposite to that of SMF, so it can compensate both group velocity dispersion and third-order dispersion simultaneously. The equation for net third-order dispersion, with UHNA-7 fiber included, is:

$$\beta_{3,TM} L_{TM} + \beta_{3,SMF} L_{SMF} + \beta_{3,UHNA7} L_{UHNA7} = 0$$

A photo of the Tm/Ho laser setup.



A simplified schematic of the types of fiber in the laser cavity.

Calculating Fiber Lengths

The length of existing Tm/Ho fiber in the laser is known: it was measured at the same time it was inserted into the laser, and that length has not been altered. The length of SMF, however, has been altered as time goes on to aid in mode-locking. The existing length of SMF fiber can be found two ways. The first is by direct measurement with a tape measure. The second is by measuring the repetition rate of the laser cavity – that is, how many times the laser pulse travels around the laser cavity per second. The length can be found from this value by solving for L in the relationship

$$v = \frac{c}{n} = \frac{L}{T}$$

where 1/T is the repetition rate. The length of SMF fiber can be found by subtracting the length of Tm/Ho fiber from the length given by the above equation.

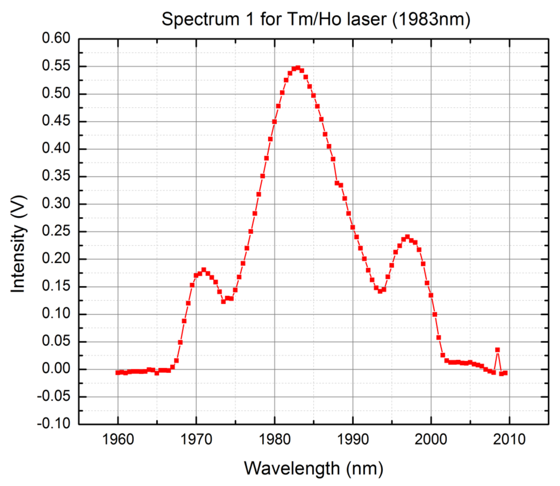
Using the formula for net cavity dispersion, we can solve for the length of UHNA-7 fiber needed to compensate the dispersion caused by the other two:

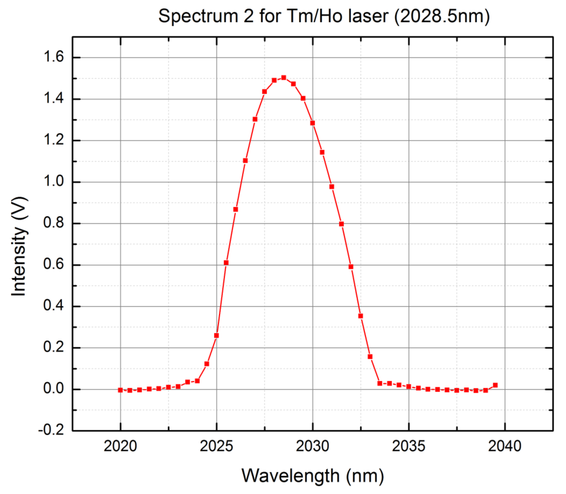
$$L_{UHNA7} = \frac{NCD - \beta_{2,TM} L_{TM} - \beta_{2,SMF} L_{SMF}}{\beta_{2,UHNA7}}$$

We have selected $0.03 ps^2$ as our desired net dispersion value. Then, L_{UHNA7}=3.05m. We can use even less of this fiber if we alter the amount of single-mode fiber in the cavity.

Spectral Data

Once the laser is mode-locked, we can take measurements to find out what wavelength(s) it is lasing at. We were able to successfully mode-lock the laser with only Tm/Ho and SMF fibers in the cavity. Since the gain fiber is doped with both thulium and holmium atoms, it can lase at 2 wavelengths, as seen by the two distinct spectra below:





The two wavelengths are found by mode-locking the laser in different polarization states.

The spectral width (FWHM) is approximately 10nm. If the UHNA-7 fiber successfully compensates for dispersion, that should get wider by about a factor of three.

Next Steps

Our next step will be to insert the UHNA-7 fiber into the laser and mode-lock it again by altering the polarization. Once this is done, we can take new spectral measurements and determine the length of the pulses, and compare these values to previous data. We expect the spectral width to be a factor of three wider than it was with solely Tm/Ho and SMF fiber.

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