A Primer on Ultrafast Fiber Lasers

Simple lasers Fiber lasers are among the simplest lasers: they don't have transverse modes, typically, and they're solid-state, with few adjustable parameters. In addition, they're made from components whose standards in uniformity and reliability have been established by the requirements of the telecommunications industry.

At the same time, the optical nonlinearities of moderately intense ultrashort pulses (~100fs) in these lasers make them an extremely rich place to discover fascinating and complex nonlinear physics. The experiments based on this laser will let you explore several regimes of nonlinear optical and laser physics.

Useful background You'll find it an advantage, but not essential, to have already done the experiments on the He-Ne laser (including modelocking) and on fiber-optics (how they work as waveguides, including single-mode waveguides, and the transverse distribution of fields). A little more important is the acoustic-waveguide experiment in this same lab-room, which leads you through pulse spreading due to group-velocity dispersion. If you haven't done the experiments, it may be useful to read the experimental guide sheets.

Advanced or specialist students may be interested to read the review paper on ultrashort-pulse fiber lasers by Nelson et al. (Nelson *et al.* 1997). Excellent books include (Derickson 1998), (Agrawal 2001) and (Boyd 1992); the first two are available through the equipment wicket, and the last is available in the Physics Library.

Advanced lab ultrafast fiber laser The fiber laser in use in the 3rd/4th Year undergraduate labs has these characteristics:

- gain medium: Er-doped single-mode glass fiber, operating broadly around 1550nm (Corning PureMode 1550C)
- pump: 980nm, 300mW cw diode laser, designed for telecom industry, 20 year lifetime (JDS Uniphase)
- modelocking: nonlinear Kerr rotation of elliptically polarized light
stretched-pulse dispersion-compensated ring
(can also be modified to operate as a soliton laser)
- dispersion: compensated principally by balanced lengths of PureMode fiber and Corning SMF-28 (opposite signs of GVD)
- output: pulse durations down to ~100 fs;
bandwidth up to ~40 nm
repetition rate ~25 MHz
average power ~2 mW

Components The components of the fiber laser serve the following functions; more detail is described in the section below about basic operation of the laser. The order of listing herre is the same as the direction of propagation of pulses around the ring.

- optical pump: λ = 980nm pump produces population inversion in Er-doped fiber

- pump input coupler: transfers pump energy from pump-input pigtail lead to output pigtail lead which is part of fiber ring; a second input lead is also part of ring, and combines 1550nm light into same output lead (wavelength-division multiplexing (WDM) component)
- Er-doped fiber: when pumped to population inversion, it produces gain. Laser pulses grow approximately exponentially in intensity as they travel

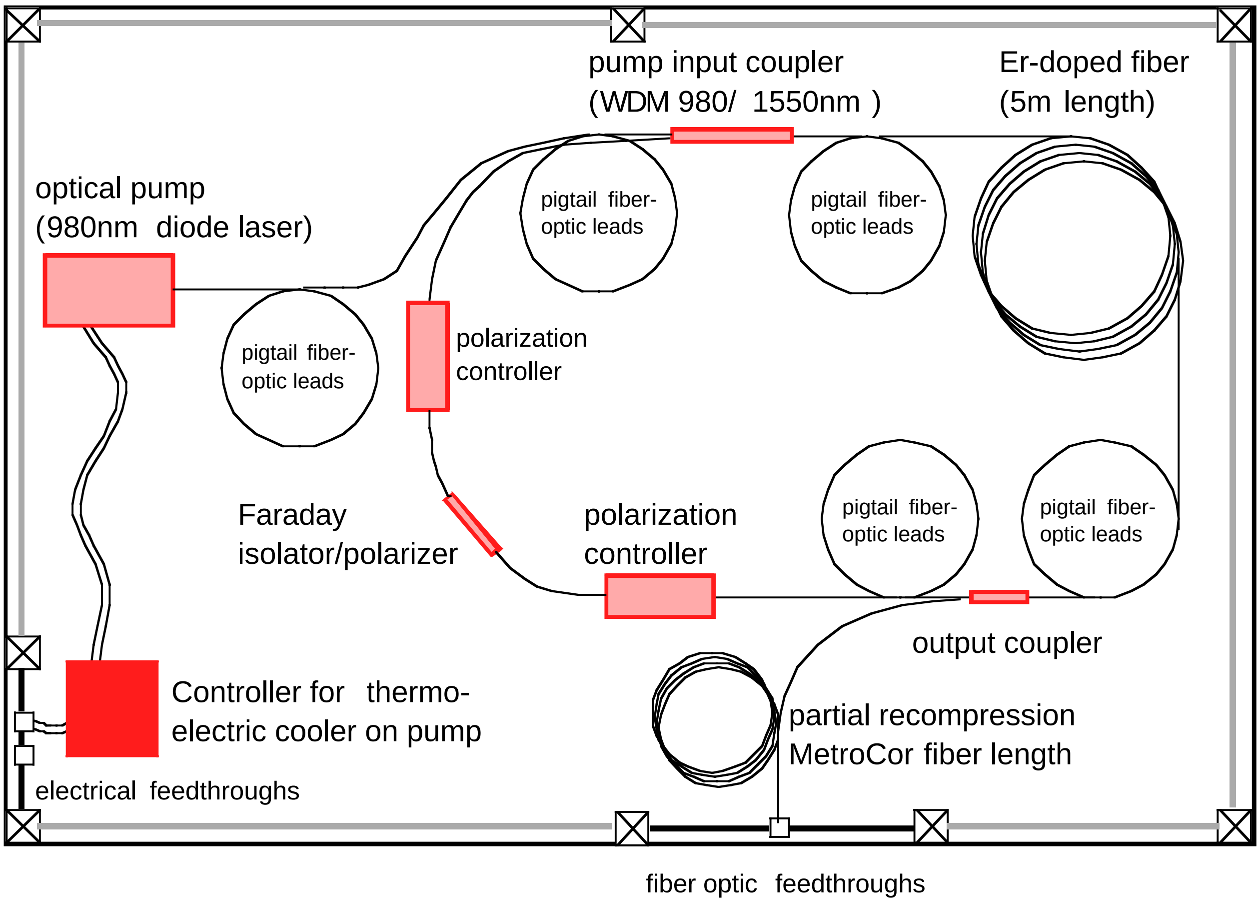

Figure 1: Schematic of the fiber laser

down this fiber. During operation, note the curious faint green glow of this fiber (room lights out), which drops off in brightness farther from the pump.

- output coupler: while the pulse travels along the fiber, from input lead to output lead, about 10% of the pulse energy is transferred to a second lead.
- partial recompress: the pulse at this point of the ring is stretched (frequency-chirped); a few meters length of MetroCor fiber has the right amount, and sign, of group velocity dispersion to partially recompress the pulse, making operation of the autocorrelator easier.
- polarization controller: the single-mode optical fiber is squeezed between steel plates, driven by a fine screw; the stress on the fiber induces

birefringence: for light polarized along the squeezed axis the index of refraction is now distinct from the index of refraction for light polarized along the perpendicular axis. For an arbitrary polarization, the two E-field *components* travel through at different phase velocities (c/n_x, c/n_y). This produces elliptically polarized light. Tightening the screw takes light from linear polarization to different ellipticities of polarization; rotating the fiber around its own axis, on the plate pivots, orients the major axis of the ellipse of the polarization.

- Faraday isolator: acts as a valve, and permits light to pass through in one direction (marked with arrow on the device); these devices may be made to be polarization-independent, but ours is also a polarizer passing a particular linear polarization.
- polarization controller: same as above. This controller actually is the 'first' one in the ring — it takes the linearly polarized light from the isolator, and prepares an elliptically polarized state. In the ring, this ellipse will rotate slightly when the light intensity is high; the controller noted above actually receives this Kerr-rotated state, and converts it back to the right linear polarization for the polarizer in the isolator. This is the basis of how pulses are formed and made ultrashort: low-intensity light doesn't rotate its ellipse enough, and dies off at the polarizer in the ellipse; high intensities survive better. So any pulses will have their low-intensity wings clipped off, but their peaks pass pretty well, and this makes the pulses shorter.
- pump input coupler: this completes the ring back to the Er-fiber, as the pump laser joins in here.

For more technical informaton about these components, see the manufacturer's data sheets, linked from the experimental guidesheet webpages; you'll also find the basics in most photonics-engineering textbooks, such as (Saleh and Teich 1991).

Principles of operation A number of interesting optical physics principles come into play in th operation of this laser. It's assumed that the reader has already been introduced to basic laser principles. This section briefly introduces the main physics issues particular to this laser, sketches operating principles, and gives references for more analytic or precise descriptions.

Elliptically polarized light — Many effects in optics depend on the management or manipulation of the polarization of light. Different linear polarizations of light can be described in terms of the amplitude ratio of components E_x and E_y, spanning all polarizations (or orientations of E) in between. But in this case, the oscillations along x and along y are in phase with each other. If the components are out of phase with each other, the trajectory of the tip of the E-field vector is no longer a straight line, linearly polarized light, but opens up to sketch an ellipse: at two points per cycle where E_x, say, is zero, E_y can be a positive value one time, and a negative value the second time. Control of the phase difference between the two components yields a whole family of elliptically polarized light modes, of which circularly polarized light is a special case: equal amplitudes in x and y, and a phase difference of 90°.

The traces which would be made by the tip of the E-field vector, for different polarizations are special cases of Lissajous figures, which you may already know from a waves and vibrations course. In this case, the frequencies are equal for the two axes, and only the amplitude and relative phase changes.

The folder on the lab computer dedicated to the ultrafast fiber laser contains a LabVIEW VI titled Polarization States Vb.vi, which will let you tinker with different combinations of amplitude and phase, to see the effects. Fig. 2 below shows some sample cases.

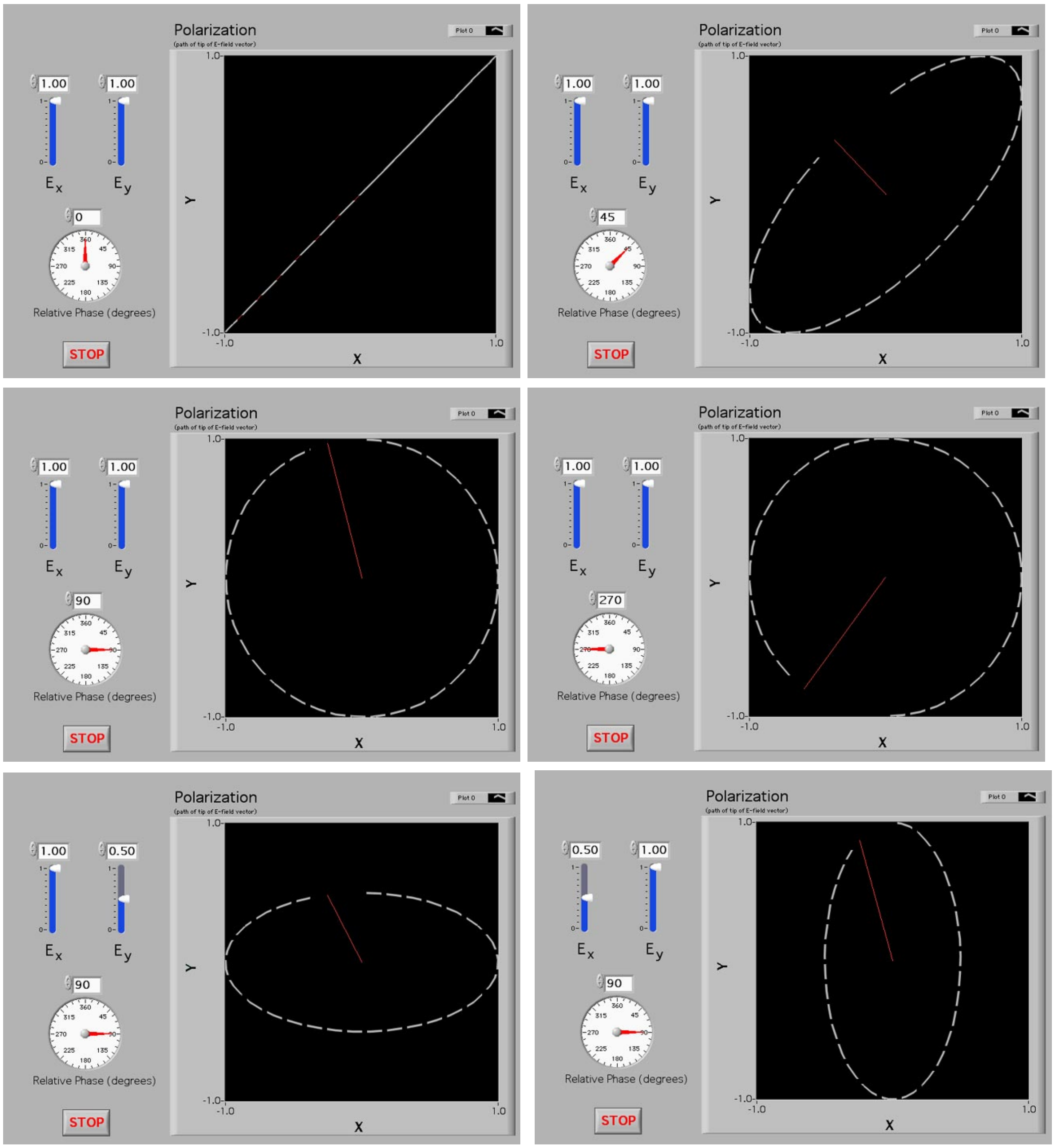

Fig. 2: Polarized light, x and y components evolving in time at a fixed position z, as light propagates towards the viewer. a) - f) across row and then below. a) linear polarization; b) elliptically polarized with major axis at 45°; c) right-handed circularly polarized, and d) left-handed circularly polarized; e) right-handed elliptically polarized light, major axis at 0°; f)

right-handed elliptically polarized light, major axis at 90°. The chirality (handedness) of the light describes the spiral made by the tip of the E-field vector: a conventional machine-screw is almost always right-handed, and is turned in by clockwise twists. Propagation of circularly polarized light is like pushing a screw forward: with right-circular light propagating towards you, the E field at a fixed plane will turn clockwise as the helix passes through.

Birefringent waveplates — The most common way of manipulating polarization is to use an non-cubic crystal or other anisotropic material, which has the property of being *birefringent*. Literally, 'birefringent' means that the material is capable of two kinds of refraction. A calcite crystal held over a printed page, for instance, will produce two completely separate images of the page, one displaced slightly sideways; the two images, in fact, are of two different polarizations. The orthogonal polarizations experience two different indices of refraction, and refract at the surface differently (according to Snell's law), making two images.

Such crystals can be used to convert linearly polarized light into elliptical polarization. the E-field of linearly polarized light travelling through will have a mathematical projection into components E_x, and E_y, which have distinct indices of refraction n_x, and n_y. The two components then have separate phase velocities $v_x = c/n_x$, and $v_y = c/n_y$. Travelling at different phase velocities, one component will drop behind the other, increasingly as they propagate through the crystal. This produces elliptically polarized light. One can cut the crystal off once a phase difference of 90° (one quarter cycle) has accumulated, and this is termed a 'quarter-wave plate'. If linearly polarized light is brought in with the E-field oriented at 45° between the axes of different index of refraction, then this will produce circularly polarized light.

Polarization Controllers — Fiber lasers sometimes use 'polarization controllers' to create an adjustable waveplate right in the fiber itself: in this case, a screw squeezes the glass optical fiber to compress the glass along one axis, which is well-known to cause a change in the index of refraction. Because the squeezing is anisotropic, the fiber ends up with different index of refraction for polarization in the direction of compression as compared to polarizations across this direction. Adjusting the compression screw therefore changes the amount of phase change imposed; rotating the miniature clamp around the axis of the fiber changes the 'fast' and 'slow' index axes relative to the polarization of light in the fiber, and so the polarization of light in the fiber can be controlled almost arbitrarily.

Kerr ellipse rotation — The index of refraction can be changed not only by physically altering the material, but even can be altered by the light itself. Almost no relation in physics is linear

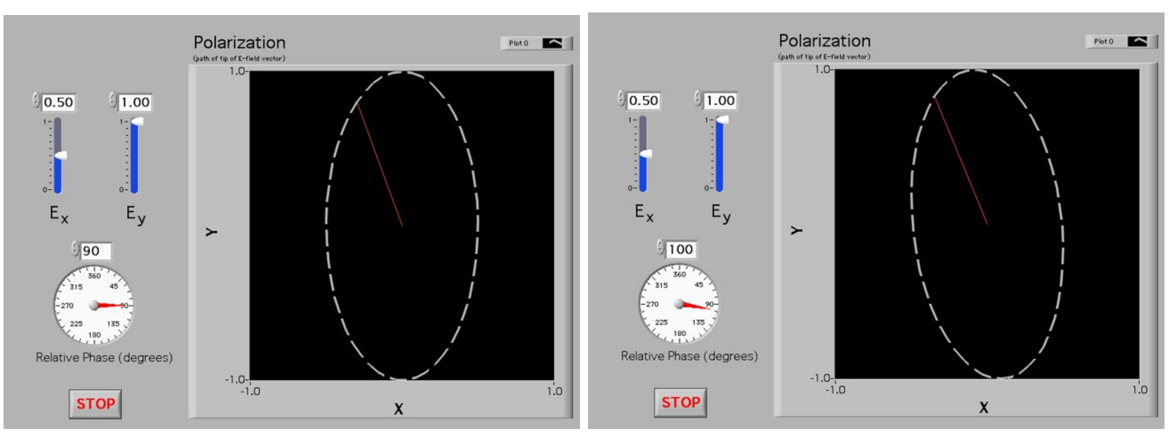

Fig. 3: Ellipse rotation due to nonlinear index of refraction; differential increments can be seen as a birefringence induced by greater intensity along major axis.

indefinitely, and the same is true for light in glass: the index of refraction depends weakly on the intensity of light, $n = n_0 + n_2 E^2$. Elliptically polarized light, then, actually sees an induced birefringence — the index is slightly higher for polarization along the major axis of the ellipse. This holds back the phase of that component of the E-field, and alters the ellipse slightly. In the demonstration software Polarization States Vb.vi, this is the same as slightly increasing the relative phase (see Fig. 3, below). The effect is to tilt the major axis of the ellipse slightly; the effect is continuous, since there is now a new birefringence along the new major axis, and so on (it isn't simply a matter of continually increasing the relative phase).

The net effect is that high-intensity elliptically polarized light, in a non-linear (Kerr) medium experiences a smooth rotation of the major axis of the elliptical polarization; this is called *Kerr ellipse rotation*.[1] This nonlinear effect is the basis of how pulses are formed in our ultrafast fiber laser. However, there is one bit of physics that remains before the picture is complete.

The simplest way to picture this effect is to note that right- and left-circularly polarized light are together basis states for all polarizations, equally as well as x and y linearly polarized light are. Consider elliptically polarized light made of strong right-handed circular light, and somewhat weaker left-circular light. The E-field for each linearly independent component is constant, then, and the right-circular light will see a slightly larger index of refraction than will the left. Thus the right-circular component will steadily drop back in phase, relative to the left-circular, and the effect is to slowly precess the ellipse made by the two together. For more information, see, e.g. (Boyd 1992)

Group velocity disperrsion (GVD) — As you may have seen in the acoustic waveguide dispersion experiment, pulses of waves travelling in waveguides (fiber optics included) suffer a temporal spreading as they propagate, because the energy associated with each frequency carries forward at a slightly different speed. The redistribution of the pulse is called 'group velocity dispersion'. In an empty waveguide, this is the result of 'modal dispersion'. Since the index of refraction of glass includes a quadratic and higher dependence on the frequency, the same effect can also be caused by the glass through which the pulse travels; this is termed 'material dispersion'. The two together determine the dispersion of a glass optical-fiber waveguide.

The implication is that any pulse of ~100fs duration we make in the fiber laser will systematically spread out with each roundtrip of the ring — and that will reduce the intensity of the pulse, wrecking the Kerr rotation we'll count on for modelocking. However, with different combinations of material (including the Er doping, and even the degree of population inversion) and waveguide (fiber) dimensions, the group velocity dispersion may be positive or negative (longer or shorter frequencies may travel faster). In an Er-doped fiber the GVD has one sign, but

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in other standard fibers, such as SMF-28, the GVD has opposite sign.[2] Therefore, we can combine the two fibers into the ultrafast fiber-laser ring, and by adjusting the relative length of each we can compensate suitably for the group velocity dispersion of the pulse, and each roundtrip the pulse returns to its minimum value (in fact, symmetry in a roundtrip requires that the pulse actually have its minimum value twice in each rountrip — once in each fiber — and the pulse passes through its minimum and out the other side within each fiber.

It is where the pulse has its minimum duration that the intensity peaks, and where the strongest Kerr rotation happens.

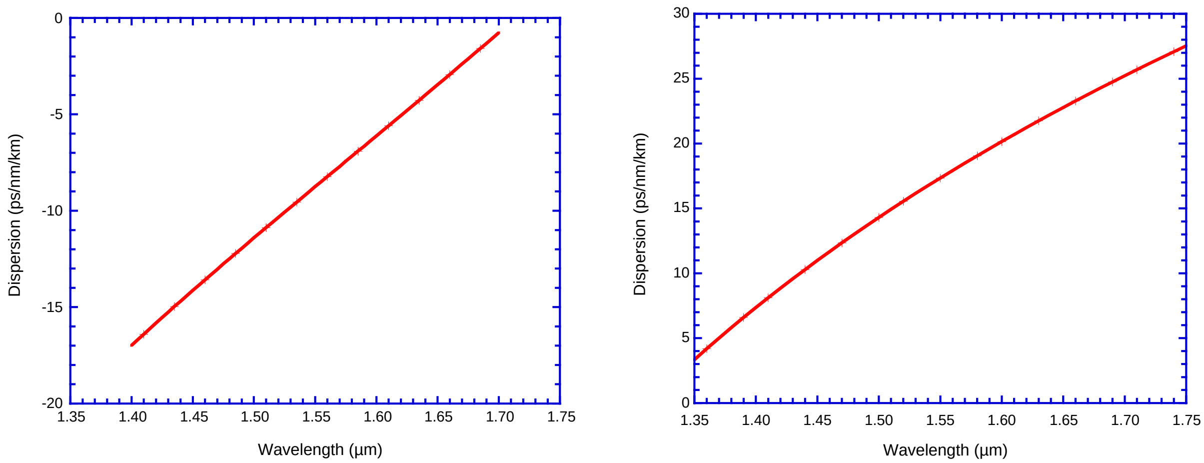

Figure 2: Group Delay Dispersion (GDD) of PureMode 1550C Er-doped fiber (left) and SMF-28 fiber (right); relative lengths of each are adjusted to control net dispersion on each roundtrip of the fiber ring.

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[2] . A word of warning about conventions and nomenclature: physicists tend to use *group-velocity dispersion* (GVD) which is typically quoted in units of $ps^2 \cdot km^{-1}$ or $fs^2 \cdot m^{-1}$; engineers tend to refer to *group-delay dispersion* (GDD) which is closely related and is quoted in units of $ps \cdot km^{-1} \cdot nm$ or $fs \cdot m^{-1} \cdot nm$, but which has the *opposite sign*.

$$GVD = k''(\omega) \equiv \left.\frac{d^2k}{d\omega^2}\right|_{\omega=\omega_o} = \left.\frac{d}{d\omega}\left(\frac{1}{v_g(\omega)}\right)\right|_{\omega=\omega_o}$$

$$GDD\ [ps \cdot km^{-1} \cdot nm] \equiv -\frac{2\pi c}{\lambda^2} \cdot GVD\ [ps^2 \cdot km^{-1}]$$

However, each refers to their quantity simply as ‘dispersion’, and so some confusion can naturally arise when even the sign of dispersion does not agree. GDD is useful in fiber-optic work because it gives you a value for pulse broadening, over a certain distance, for a pulse with a given bandwidth.

Positive GVD is said to produce *positive* or *normal* dispersion (red components travel faster than blue ones). For negative GVD we say that the material or waveguide has *negative* or *anomalous* dispersion. The signs GDD, of course, are reversed for normal and anomalous dispersion.

Stretched-pulse ultrafast fiber lasers — the operating story

With this grasp of all the components and physical principles, we can now give a good, though rather heuristic, description of how modelocking in this stretched-pulse ultrafast fiber laser works.

As in all laser oscillators, there is spontaneous emission from the active medium into the optical modes of the resonator. In our case, we have millions of longitudinal modes that are cyclic or periodic over one roundtrip of the fiber ring; transversely, the fiber optic supports only a single mode: the lowest, or fundamental transverse mode. The laser pulse has its origins in the statistical fluctuations in intensity of this spontaneous emission, wherein only the highest-intensity peaks in the optical 'noise' are able to survive a roundtrip in the ring, and see repeated amplification until a steady state is reached.[3] The rest of this section will be about the details of how that is possible.

Picture an optical pulse starting from the polarizing isolator: at this point, we know the direction of light propagation, and we know the polarization state is precisely linear, along a well-defined axis. This linearly polarized light propagates to the polarization controller, where it encounters an adjustable birefringence (as the screw is tightened or loosened) and an adjustable axis for the orientation of the birefringence 'slow' axis. By adjusting the degree of birefringence, and the orientation of the resultant waveplate, the linear polarization can be converted to elliptical polarization.

Neglecting any other effects, for the moment, this elliptically polarized light can travel around the fiber ring, be amplified in the Er-doped segment, and arrive at the second polarization controller. This polarizer can be adjusted in such a way as to exactly cancel th effects of the first waveplate, restoring the linear polarization state which will transmit without loss through the polarizing isolator.[4] In that case, low-intensity light will have very little loss in a roundtrip; the gain in the optical amplifier, in fact, means that light intensity will grow on each roundtrip, and the laser will operate in continuous-wave (cw) mode at a steady intensity.

This doesn't make a modelocked ultrafast laser, of course. That happens because of the intensity fluctuations which are the germ of the pulses we wish to amplify. Consider such a rapid fluctuation, in a forest of random 'white noise', starting at a place in the ring roughly halfway around from the middle of the Er-doped fiber segment. This tiny pulse will travel along the optical fiber (mostly SMF-28), and suffer anomalous dispersion, which will make it stretch out and chirp so that the highest frequencies arrive first with lower frequencies following. As the pulse stretches in time, of course, the intensity drops. Once the stretched-pulse leaves the SMF-28 fiber, it enters the Er-doped amplifier segment of fiber — which has normal dispersion. As the pulse travels and is amplified, the opposite dispersion also causes the pulse to compress, and the intensity to go up concomitantly. Around the middle of the fiber, the pulse is at its shortest and most intense. After that point, the continuing normal dispersion makes the blue and red components 'pass through' each other, in rough terms, and the pulse becomes progressively

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[3] In the matter of statistical fluctuations, you may recall the story of the mathematician who drowned in a creek that had *average* depth of six inches...

[4] In fact, there is always some incidental birefringence in the optical fiber, mostly from coiling the fiber into loops for storage, so the elliptically polarized light may be altered a little on a roundtrip. The second polarization controller can correct for this.

more stretched and chirped, with red frequencies leading now, and blue ones following. Entering the SMF-28 fiber once again, the dispersion is reversed, and the pulse compresses once more until it returns back to its original position; if the lengths are approximately matched, the pulse will return with approximately its original duration.

To this, we now add the nonlinear phenomenon of ellipse rotation, introduced above. Where the pulse is at its shortest duration, and therefore its highest intensity, there's a concentration of the effect: The major axis of the elliptically polarized light then precesses slightly — the elliptical polarization twists somewhat as the light propagates — so that when the intense part of the pulse arrives at the second polarization controller, it is converted to the *wrong* polarization state for getting through the polarizing isolator. Therefore, energy is lost for the peaks of the most intense fluctuations; if more energy is lost here than is gained in the amplifier, then the pulse will die out. In this way, the fiber laser settings force it to run *cw*, and actively discriminate against formation of pulses.

However, it is a simple matter to alter the settings of this second polarization controller, so that it will 'catch' or recover the *ellipse-rotated* state, and convert it, and not the original polarization state, into the linear polarization state suitable for passing through the polarizing isolator. In this way, intense peaks of fluctuations can have the least loss at the polarizer, and so will have the highest net gain per roundtrip — they will have the fastest growth in the laser. Cw operation, weaker pulses, and even the leading and trailing edges of intense pulses, will not cause enough ellipse-rotation to match this new setting, and so will be relatively attentuated.

This amounts to suppressing the leading and trailing edges of pulses, and growing the central peaks disproportionately. By this, the pulses get narrower in duration until ultrafast pulses of about 100 fs are produced.

Limitations, and some quantification

What sets a limit on this process? Why does it not produce shorter pulses? Several factors eventually come into play.

One issue of course is true for all waves: that time and frequency are *conjugate*. An oscillation sin(ωt) has a purely defined single frequency, but exists for all time from $-\infty$ to $+\infty$. Limiting the duration of the waveform in any way will introduce new frequencies; the formula for this is found in Fourier analysis (a discrete series) for periodic functions, or in Fourier transforms (a continuous function) for non-periodic functions:

$$\Delta t \cdot \Delta \nu \geq 1$$

where the precise value on the right-hand side depends on the definition of Δ, the metric for defining the duration or width.[5] For a gaussian pulse in time, the spectrum is gaussian in frequency, also; when Δ is taken from the FWHM, the formula becomes:

$$\Delta t \cdot \Delta \nu \geq 0.44$$

[5] Some standard metrics include the full-width at half-max (FWHM), the full-width at 1/*e* of max, and the r.m.s. variation of the function. It isn't surprising that this is the formula also of the Heisenberg Uncertainty Principle, since quantum mechanics derives from wave properties. Note that $\Delta E = \Delta(h\nu) = h\Delta\nu$, so, again roughly, our formula above gives $\Delta E\ \Delta t \geq h$.

When the product has its minimum value (equal to the right-hand side) the pulse is said to be *transform-limited*: the pulse is as short as it can be, consistent with its Fourier transform giving the spectral bandwidth.

In any laser, the spectral range of the gain (*gain bandwidth*) will limit the range of frequencies any pulse may have, and so limits how short a pulse can be ultimately produced. The matter is a little complicated by the fact that one considers not the FWHM of the whole gain-curve, but only the part in excess of losses; further, when the pulse passes through the gain-mediumsomething like 100 times, say, it becomes a matter of the FWHM of the net-gain curve to the 100th power, *i.e.*, $(\gamma(\nu))^{100}$, which for a gaussian gain-curve is something like 10% of the FWHM of the gain curve. This reduction in the spectral bandwidth is termed *gain-bandwidth narrowing*.

Other phenomena may add to this, or compete with this. One that can compete is the nonlinear phenomenon of *self-phase modulation*, which can be heuristically explained as follows. We've seen already that the index of refraction depends also on the intensity of light. This means that on the rising edge of a laser pulse, each successive wave crest, at progressively higher intensity, sees a slightly larger index of refraction. Therefore the phase speed is slightly slower for each successive wave crest on the rising edge:

$$v_\phi(I) = \frac{c}{n(I)} = \frac{c}{n_o + n_2 E^2}$$

So, each successive wavefront cannot quite keep up with the preceding wavefront, and the wavelength between crests increases slightly — the freqency becomes red-shifted. Conversely, on the trailing edge of the pulse, wave crests pile up slightly, and the instantaneous frequency is blue-shifted. The greatest effect for both occurs where dI/dt is greatest in magnitude within the pulse.

By this, intense ultrafast pulses in nonlinear materials can actually pick up extra bandwidth, even where the pulse is not being shortened by modelocking effects. Moreover, the pulse ends up with a small overall frequency chirp, which can be compressed with some success by anomalous dispersion in a fiber such as SMF-28.

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