Ultrashort Pulse Fiber Lasers

BY IRL N. DULING III

For years people have been looking for a compact, electrically efficient, inexpensive source of optical pulses less than one picosecond in duration for scientific investigation, optical probing, and, more recently, for high bit rate communication or computing systems. The early promises of modelocked diode lasers fell prey to low reliability and large intrapulse frequency chirp. When the first single-mode rare-earth-doped optical fiber was drawn in 1973, no one could predict the impact that this development would eventually have. Since then, we have seen fiber become the preferred method of communications transmission, and the rare-earth-doped optical fiber the preferred method of optical amplification. It is not surprising, then, that there has also been a significant effort to use the wide bandwidth of the rare-earth-doped fiber gain transition to make a laser to produce ultra-short pulses. In its most elegant form, this laser would be all fiber, diode laser pumped, and capable of producing pulses of less than half a picosecond.

Advancements in several fields have fueled active research and made this laser a reality. The development of low loss rare-earth-doped fibers, the understanding of nonlinear propagation in fibers, the proliferation of fiber components to support the rapidly advancing optical communications industry, and the concurrent work on wide bandwidth solid state lasers all contributed to the research efforts producing a variety of short pulse fiber lasers.

Fiber Laser Considerations

Fiber lasers have several characteristics significantly different from bulk solid state lasers. Except for the laser diode, the rare-earth-doped fiber is the only high gain solid state material. With small signal gains of up to $10^4$, the fiber laser can tolerate significant cavity losses. Output couplers consisting of the cleaved end of the fiber (4% reflection) are not uncommon. Lossy components such as grating pairs, integrated-optic modulators, and optical isolators can be inserted with relative ease. The down side of this high gain is that a significant amount of power can be extracted from the fiber with no mirrors at all by amplified spontaneous emission, and the effect of spurious reflections can be significant.

The fiber laser with its high field confinement is also a perfect candidate for nonlinear optical effects to become significant. The handling of the nonlinear effects in the cavity may well determine the ultimate pulsewidth obtainable for many fiber systems. As is well known, the propagation of a pulse in an optical fiber is dominated by two effects: group velocity dispersion (GVD) and self-phase modulation (SPM). Self-phase modulation is the generation of higher frequencies on the trailing edge of the pulse, and lower frequencies on the leading edge due to the time varying refractive index caused by the pulse intensity. Since in that wavelength range the higher frequencies travel more slowly and the lower frequencies more quickly (GVD), the pulse will disperse. At wavelengths shorter than the zero dispersion point of the fiber (typically 1.3 μm), GVD and SPM will work together to disperse the pulse. In contrast, wavelengths longer than the zero dispersion point, the sign of GVD is reversed and the higher frequencies on the trailing edge catch the pulse, that overtakes the slower moving low frequencies. This process can produce stable pulses that propagate without changing shape, known as solitons. At the shorter wavelengths, proper compensation of dispersion can lead to more routine pulse compression (with SPM physically separate from the compensating GVD).

By far, the majority of fiber lasers have been constructed from standard, non-polarization-preserving fiber. This means that every fiber laser supports two orthogonal laser modes. In certain cases, this can be used to advantage. The same nonlinear propagation discussed above can lead to intensity dependent polarization rotation. Properly adjusted, and with a polarization controller, this nonlinear polarization rotation can be used as a fast saturable absorber.

Another contrast between fiber lasers and the bulk lasers is that for many fiber lasers there are very few adjustments that can be made once the cavity is assembled. In a simple all-fiber laser, the only adjustment is launching of the pump light into the pump coupler fiber (and even this is eliminated with the use of a pigtailed laser diode as the pump source). All that remains is to adjust the pump power and look at the output. Most fiber systems, however, are not this simple. Usually there are polarization sensitive components in the laser. Therefore, a polarization controller must be added. In addition, active components require some electrical drive. The "knobs" on a fiber laser are significantly different from those on a bulk laser.
The first rare earth-doped-fiber lasers were based on Nd:glass. A wide variety of modelocking schemes have been used; saturable absorbers, amplitude and phase modulation, nonlinear mirrors, and nonlinear pulse compression. The reasons for the early interest in the Nd-doped fiber laser were practical and scientific. Nd:glass is a well characterized laser material, and the 1.06 mm wavelength region is a common one so that optical components were readily available. In addition, the four level structure of the Nd laser provides a low pump threshold for lasing and absorption bands exist that allow pumping by AlGaAs laser diodes, R6G dye lasers, argon ion lasers, Ti:sapphire lasers, and flashlamps.

A typical actively modelocked Nd:fiber laser is presented in Figure 1. This type of laser has produced pulses as short as 70 psec for amplitude modulation, and 20 psec for phase modulation. The amplitude modulated laser had a diode pumped output power of 10 mW. To remove the difficulty of optical coupling to the modulator, integrated fiber modulators have been incorporated into these lasers with some success, producing pulses around 60 psec.

A major consideration when working at 1 μm is the group velocity dispersion in the fiber. A typical value of dispersion at this wavelength is 50 psec/nm-km, which for a bandwidth of 30 nm and a fiber length typically about 1 m leads to a broadening of 3 psec/round trip. To compensate for this dispersion, gratings or prisms have been added to the cavity. Besides compensating for the linear dispersion of the cavity, when combined with the self-phase modulation in the fiber, the compensation can work to shorten the pulse through the same process as standard fiber pulse compression.

The most recent advance in modelocked Nd:fiber lasers has been the inclusion of a nonlinear mirror in the cavity of the laser. Conceptually, this is a mirror that has an increasing reflectivity for increasing incident intensity. When a pulse reflects from a nonlinear mirror, the wings of the pulse are clipped due to the reduced reflectivity, causing a reduction in pulsewidth. One such mirror that was included in the Nd:fiber laser is the nonlinear amplifying loop mirror (NALM). When incorporated in the dispersion compensated fiber laser, pulses as short as 125 fsec were obtained. A second nonlinear mirror based on nonlinear polarization rotation has led to the current record for the shortest pulse from a Nd:fiber laser of 38 fsec. This is also the first modelocking of the full inhomogeneously broadened bandwidth of a laser material.

By far the most work, however, has been done on the Er-doped fibers. This interest has been driven because the lasing transition is situated in a low loss window of optical fibers (1.5 μm) and because of the possibility of soliton formation to aid in pulse shortening. With the latest generation of optical communications being designed at 1.5 μm, the recognition that an Er:fiber-based source would provide the ultimate system compatibility for fiber communications also served to fire the research.

The first modelocked Er:fiber lasers were actively modelocked and produced pulses of about 100 psec. The first indication that much shorter pulses could be obtained came when Kafka et al. added approximately 2 km of standard telecommunications fiber to an actively modelocked ring fiber laser to produce 4 psec pulses. One advantage of this style of laser is the lack of bulk components. Figure 2 shows a typical fiber ring laser with an integrated optic modulator as the modelocker. Since then, the same cavity configuration has been optimized using diode laser pumping to obtain 2.8 psec pulses. A similar configuration has also produced up to 30 GHz pulse trains, demonstrating the ability of these systems to generate high bit rates. In the
linear configuration similar to Figure 1, the Er:fiber laser has shown definite soliton pulse formation\(^\text{18}\) and produced pulses of 0.9 psec\(^\text{19}\) but displays an instability of pulse relative timing if more than one pulse is present in the cavity.\(^\text{20}\) It has been shown theoretically that even though the amplitude of the pulse is widely varying over a cavity round trip, stable soliton solutions can be established in the laser if the cavity length is much shorter than the soliton period.\(^\text{21}\)

To address the need for wavelength tuning, of the modelocked laser for wavelength division multiplexing, frequency selective elements have been added to the laser cavity. Although this bandwidth limitation will increase the pulse duration, the pulses are still short enough to be useful. Several tuning methods have been used: bulk gratings,\(^\text{11}\) integrated fiber Bragg gratings,\(^\text{22}\) angle tuned interference filters,\(^\text{23}\) and fiber birefringence.\(^\text{24}\)

**Figure Eight Laser**
The shortest pulses in modelocked Er:fiber lasers have, as in the Nd:fiber, been produced when passive modelocking has been employed. The first passive modelocking was done with a nonlinear optical loop mirror (NOLM)\(^\text{25}\) and produced square pulses with a minimum duration of about 200 psec.\(^\text{26}\) By including the amplifier into the loop mirror, creating a NALM, a number of groupsec have demonstrated short pulses in what has become known as the "Figure Eight Laser" (F8L).\(^\text{27}\) Shown in Figure 3, this laser has been the subject of intense research. Developed simultaneously by two different laboratories in independent research efforts,\(^\text{27,28}\) this laser became the first Er:fiber laser to produce subpicosecond pulses.\(^\text{29,30}\) Similar lasers were also proposed theoretically at about the same time.\(^\text{31,32}\) This laser has been pumped by a laser diode,\(^\text{33}\) can be self-starting,\(^\text{34}\) and is stable enough to use in probing experiments.\(^\text{35}\)

The optical arrangement of the F8L is that of a NALM, with its output coupled back into its input. As a pulse is incident on the properly adjusted NALM, the high intensity portions of the pulse are transmitted, and the low intensity portions are reflected. The optical isolator in the cavity removes the reflected portion of the light from the cavity. An output coupler in the external loop extracts the pulse from the cavity. The F8L has produced pulses as short as 290 fsec,\(^\text{36}\) and repetition rates as high as 125 MHz.\(^\text{37}\) The repetition rate, as in the actively mode-locked soliton lasers,\(^\text{20}\) is often indeterminate. Due to the ultrafast switching of the NALM, independent pulses spaced as closely as 14 psec (indicating a repetition rate of 71 GHz) have been reported.\(^\text{38}\) In general, since the laser is passively modelocked, there is no external input to dictate the phase of the emitted pulse train. This is true only not only when there is one pulse in the cavity, but as additional pulses are produced, there is nothing in the design of Figure 3 to dictate the relative spacing of each additional pulse. The pulse train is often formed as bunches of pulses. These pulses move relative to one another, due to amplitude or frequency differences, within the bunch.\(^\text{39}\) Several solutions to this problem have been presented. The first was to include a second gain medium that had a large amount of gain saturation\(^\text{40}\) (a semiconductor laser amplifier). This saturation causes the lowest loss condition to be when the multiple pulses are as far apart in time as possible. Another solution is to include in the cavity a mechanism to multiply the repetition rate to a high multiple of the cavity round trip with a subcavity.\(^\text{41}\) By adjusting the pump power (and therefore the saturation power of the amplifier), the laser can be adjusted to produce only enough pulses to fill the cavity once. There are still some questions regarding the operation and optimization of this laser. The pulses propagate as solitons, and have been demonstrated to have quantized energy.\(^\text{27,39}\) It is also possible to compress these pulses by using soliton propagation in a fiber outside the laser. This has been demonstrated to produce pulses as short as 50 fsec with some pedestal.\(^\text{42}\)

Another passive modelocking technique for an Er:fiber laser is to sandwich an InGaAs/GaAs-on-GaAs superlattice in a rotary splice to produce an integrated fast saturable absorber.\(^\text{43}\) This method produces a bidirectional subpicosecond ring fiber laser with pulses as short as 377 fsec.\(^\text{44}\) The laser can be pumped by a laser diode, is self-starting, and generally produces a single pulse spaced by the cavity round trip time.

**Pulsewidth Limitations**
Soliton propagation has the characteristic that a shorter pulse requires a higher energy per pulse. As the pulses from soliton forming fiber lasers become shorter, the peak power of the pulse increases dramatically. As the peak power increases, nonlinear effects become more significant. One such effect that must be considered is that of the soliton self-frequency shift (SSFSEC). As the pulse propagates down the fiber, gain is generated on the long wavelength side of the pulse due to the Raman effect. With the wide bandwidth of the optical pulse overlapping the Raman gain, there is a pulling of the pulse central frequency to longer wavelengths. In extreme cases, the shift might be large enough to pull the pulse out from under the Er:fiber gain window. It is possible that this is the bandwidth limiting effect in the erbium-doped fiber lasers, preventing the utilization of the 30-60 nm of bandwidth available.

Other bandwidth limiting effects might be fiber birefringence with a polarizer acting as a Lyot filter in the system, intentional or unintentional Fabry-Perot filters in the
cavity, or higher order terms of dispersion effecting the soliton forming processes in the cavity.

CONCLUSIONS
The rapid advancement in the field of fiber lasers over the past two years is evidence of the great interest that is generated by the prospect of a compact, inexpensive, and efficient source of subpicosecond pulses. Large strides toward this end have been made and it is likely that the next few years will see commercialization of these lasers. The most likely application is in the area of optical probing of materials, but there is also great potential application in the area of high bit rate communications. Here systems with pulse lengths in the tenths of picoseconds will see application first, whereas the shorter pulse systems will see application in the next generation of ultra-high bit rate short haul communications.

The field of modelocked fiber lasers is still rapidly evolving. New cavity configurations and new modeling processes are being actively developed as each new active or passive fiber component becomes available. The fiber laser will someday allow femtosecond research to be carried out without the need for large, inefficient, expensive laser systems, and provide the basis for widespread application of ultrashort pulses.

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REFERENCES