modes each of which at high powers develops a field maximum in one of the nonlinear media.[7] Branch D also contains two modes in each of which one of the field extrema associated with TE_1-type modes moves into a nonlinear medium at high powers.[7] Branch E is characterized by $z_1 = -z_3$ and occurs when $\kappa k_0 d = m\pi$, where m is an integer. The dispersion curve for E starts with $z_1 = z_3 = 0$ at its intersection with curve C, rises with increasing power until it reaches curve D and then falls to its lowest power value. Along this curve, the field maximum moves successively further into the appropriate nonlinear medium.

All of the above phenomena occur in the 10–100's milliwatts range with liquid crystal media and should be experimentally realizable. Device applications appear possible in the area of optical limiters and optical bistability.

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Generation and measurement of optical pulses as short as 16 fs

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We describe measurements of pulses consisting of only eight optical periods. The pulses were produced by compression with a short optical fiber and a grating pair. Measurement was by autocorrelation using noncollinear second harmonic generation in a thin crystal of potassium dihydrogen phosphate.

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Considerable progress is currently being made in the generation of ultrashort light pulses. Extension of subpicosecond, passively mode-locked dye laser technology[1] to the colliding-pulse (CPM) ring geometry[2] was the first method to result in a reliable, direct source of pulses shorter than 100 fs. Now with nonlinear optical fiber techniques[3,4] it is possible to reach this time domain[5] by compressing the picosecond pulses emitted by a variety of other lasers. Pulse shortening to 37 fs has also recently been achieved by parametric scattering of amplified CPM dye laser pulses.[6] Nevertheless, the shortest pulses to date (30 fs) have been achieved by fiber compression of amplified pulses from a CPM based system.[7] We report here extension of this latter technique to the generation of yet shorter (16 fs) pulses. These pulses, with a center wavelength of about 620 nm, are comprised of only eight optical periods.

The femtosecond pulse source for our compression experiments is a CPM ring dye oscillator[2] which produces pulses as short as 55 fs, as previously reported.[8,9] We have found this to depend somewhat upon the age of the mode-locking dye (DODCI), with pulse duration lengthening to 60–65 fs after a week or so of operation. Single pulses from this oscillator are selected and amplified at a repetition rate of 10 Hz by the first two stages of a high-power, femtosecond dye amplifier chain.[10] The pulses, after two stages of amplification and saturable absorption, have been amplified by a factor of about 5×10^4 to energies of 5 μJ. For an improved spatial profile, the output beam is spatially filtered by focusing through a 50-μm pinhole and is then collimated to a diameter of 6 mm. Pulse spreading due to the amplifier stages is compensated after the spatial filtering by a grating-pair compressor[11] comprised of 600 ℓ/mm gratings separated by a slant distance of about 2.5 cm. Part of the beam is split off at this point and detected with a photodiode to monitor pulse energy.

Thus prepared, the pulses are coupled into a short (8 mm), length of polarization preserving optical fiber[12] with a 10$\times$ objective. Power in the guided mode is adjusted by simply moving the objective in and out of focus. A HeNe alignment laser is also used to facilitate alignment of the fiber and subsequent optics. Pulses emerging from the output end of the fiber are imaged with a 40$\times$ objective through a 100-μm pinhole to filter out cladding modes. The beam is then recollimated to a diameter of 3 mm.

Spectral broadening produced by passage through the fiber is monitored with an optical multichannel analyzer. Under the operating conditions for this experiment, about 5 nJ of pulse energy coupled into the fiber mode, the input spectrum is broadened by a factor of about 4. The change in color is visibly apparent. As the input energy is increased, the spectrum broadens smoothly into a continuum. For short fibers, however, this is also close to the damage threshold.

Final recompression of the pulses is performed with a pair of 600 ℓ/mm gratings separated by a slant distance of about 1.5 cm. Adjustment of this pair also precompensates for dispersion in the autocorrelator. Parallelicity of the grating surfaces can be adjusted by long distance projection or other spatial filtering. Misalignment can be seen as a separation of colors in the far field and by a lengthening of the autocorrelation function. The relative rotation of the grating rulings was also found to be surprisingly critical. A diameter of at least 3 mm on the gratings is required to avoid noticeable effects of spectral walk off. It is interesting to note in this context that there is a maximum compression that a grating pair can provide without spectral walk off:

$$\Delta\tau \ll N\lambda / c. \tag{1}$$

That is, the maximum $\Delta\tau$ is limited to approximately N optical periods, where N is the number of grating lines illuminated by the beam.

Measurement of the compressed pulses is performed by autocorrelation using the conventional background-free, noncollinear SHG method.[13] This is done to avoid the problems associated with obtaining, at the 10-Hz pulse repetition rate, a proper average of the nonlinear coherence fringes in a collinear experiment. As a result, some geometrical broadening is certainly introduced into our measurements. We attempt to keep this broadening at a minimum by making the angle between the two beams as small as possible and focusing to a common, diffraction-limited spot. For our experiments, in which this angle is 2 deg and the pulse durations are 16 fs, we estimate the geometric broadening effect to be less than 1 fs.

To minimize dispersive effects that cannot be compensated, only front-surface aluminum mirrors are employed in the modified interferometer used for the autocorrelation measurements. Since the mandatory beam splitter introduces a 1-mm thickness of glass into one of the interferometer beams, a plate of similar thickness is inserted into the other beam to restore a dispersive balance that can be compensated by the gratings. The two parallel but noncollinear beams exiting from the interferometer are focused into the nonlinear crystal with a 15-cm focal length achromatic lens.

A 0.1-mm-thick KDP crystal, oriented for phase-matched SHG at 620 nm, is mounted with UV transmitting cement on a quartz plate.[14] It is positioned with the crystal toward the incident, fundamental beams. Dispersive spreading of the fundamental pulses in transit through the 0.1-mm crystal is calculated to amount to less than 1 fs. Recent theoretical analysis has shown that a measurement of bandwidth-limited pulses is not critically sensitive to either group velocity dispersion between the fundamental and second harmonic or limitations on the phase-matching bandwidth.[15] Nevertheless, the thin crystal minimizes these effects. Tight focusing also increases the phase-matching bandwidth. The SHG is detected with a photomultiplier apertured to discriminate as much as possible against individual beam background. Too small an aperture would also filter out desired, off-axis, SHG frequency components.

Relative delay between pulses in the autocorrelator is varied with 0.1-μm/step, digitally controlled translation stage in one of the interferometer arms. Scanning is done unidirectionally to eliminate backlash. Reasonably smooth autocorrelation traces are obtained by averaging 2 scans of 5 laser shots per 0.2-μm increment. Large fluctuations in input pulse energy are eliminated electronically from the averag-

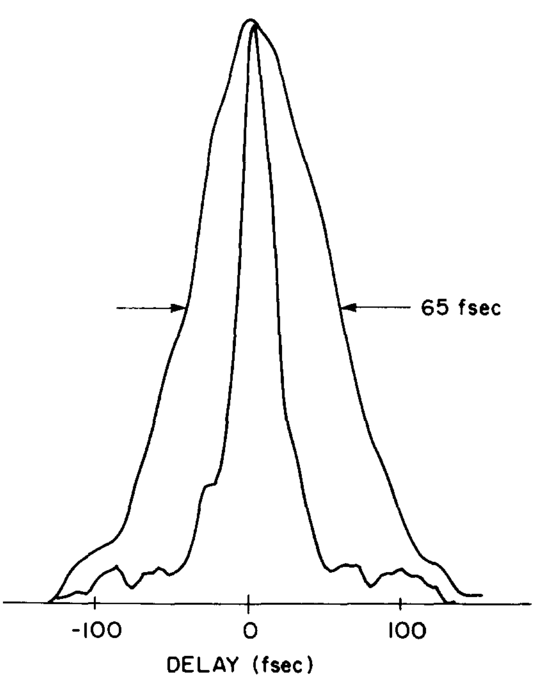

FIG. 1. Intensity autocorrelation traces of pulses before and after compression. The horizontal axis indicates the zero intensity level and relative beam delay in the autocorrelator. The 65-fs width (FWHM) of the input pulse assumes a sech^2 shape.

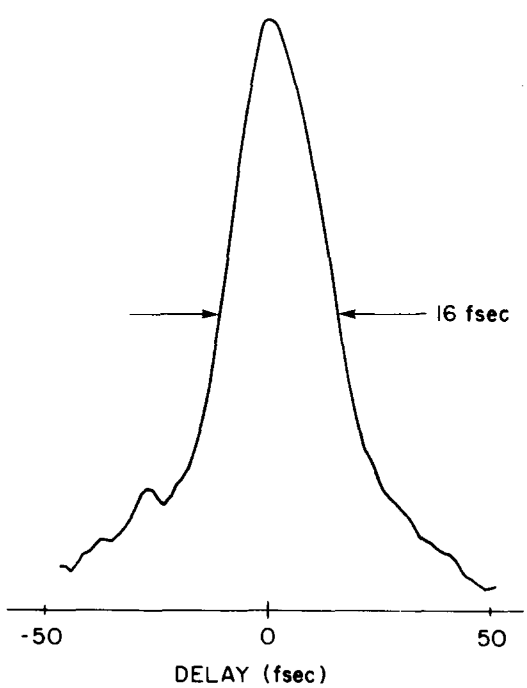

FIG. 2. Expanded and more closely sampled autocorrelation measurement of the compressed pulses. The horizontal axis indicates the zero intensity level and relative beam delay in the autocorrelator. The 16-fs width (FWHM) assumes a sech^2 shape.

ing process with a discrimination of about $\pm 15\%$. Sensitivity of the measured pulse duration to input energy fluctuation is found to be considerably greater for our 16-fs pulses than for those only a factor of 2 longer. This may be due to changes in amplified pulse shape with energy.

Figure 1 shows a measurement of compressed pulses superimposed upon a measurement of input pulses from our two-stage amplifier. The input pulses are about 65 fs in duration full width at half-maximum, assuming a sech^2 pulse shape. Compression by a factor of 4 is apparent and relatively unaccompanied by energy in the wings of the short pulse. Figure 2 illustrates a similar measurement of the compressed pulse alone on an expanded and more closely sampled scale. The indicated 16-fs pulse width again assumes a sech^2 shape. Pulse coherence is corroborated by the measured time-bandwidth product $\Delta\nu\cdot\Delta t = 0.43$.

Finally, it is important to note that pulse generation, compression, and measurement with the system we have described have been very reproducible. The experimental traces shown in Figs. 1 and 2 are in fact typical representatives of the many traces obtained which indicated pulse durations in the range 15–17 fs. With our present system, an extension to higher powers and shorter fibers has not yet resulted in pulses shorter than 15 fs. Further advance may require still more careful tailoring of input pulse shapes as well as compensation of higher order propagation effects in the fiber, the compressor, and other optical elements.

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Single-longitudinal-mode GaAs/GaAlAs channeled-substrate lasers grown by molecular beam epitaxy

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We present here the first simple double-heterostructure channeled-substrate laser with lateral index guiding grown by molecular beam epitaxy. The channel is along [110] direction. The threshold current is 60 mA. Linear light-current relation and stable far-field patterns have been observed over the range of currents tested (from 60 to 160 mA). The lasers operate in single longitudinal mode over a wide range of current. The intensity ratio of the dominant mode and the neighboring mode is greater than 100:1.

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In the past few years, considerable effort has been devoted to controlling modal behavior in semiconductor injection lasers, and much progress has been achieved.[1–4] Channeled-substrate (CS) GaAs/GaAlAs injection lasers, which exhibit a linear light versus current relation, a stable far-field radiation pattern, and a single longitudinal-mode operation over an extended range of the laser power, have been realized by liquid phase epitaxy (LPE)[5–7] and metalorganic chemical vapor deposition (MOCVD).[8] The main advantage of the channeled-substrate structure compared to other laser structures with built-in optical waveguide is the simplicity of the fabrication process. So far, molecular beam epitaxy (MBE) has demonstrated its superior ability in growing planar, uniform layers for the devices. It has been shown[9] that the growth characteristics with MBE are different from those of LPE. In the present experiment, MBE is utilized to grow $GaAs/Ga_{1-x}Al_xAs$ double heterostructure lasers over preferentially etched channels along the [110] direction on a (001) oriented GaAs substrate. Results obtained from this experiment show that single-longitudinal-mode operation of $GaAs/Ga_{1-x}Al_xAs$ double-heterostructure channeled-substrate lasers can be obtained by MBE. In another experiment when $[1\bar{1}0]$ oriented channels were used, the threshold current was found to be higher. It is believed to be caused by the defects in the epilayers due to the intersections between the rearranged crystal planes.[9] For channels aligned along the [110] directions, there are two overhanging edges on the two sides of the undercut channels. In order to prevent shad-

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