Tunable InGaAsP Lasers for Spectral Measurements of High Bandwidth Fibers

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Abstract—**An ultrashort-cavity thin-film laser of InGaAsP, pumped with a mode-locked and *Q*-switched Nd:YAG laser, has been used as the source and an InGaAs/InP p-i-n photodiode as the detector to demonstrate a system capable of measuring bandwidths of 8.5 GHz in single-mode optical fibers. The film laser emits pulses shorter than 10 ps and is tunable over 1700 Å near the chromatic dispersion minimum in fibers.**

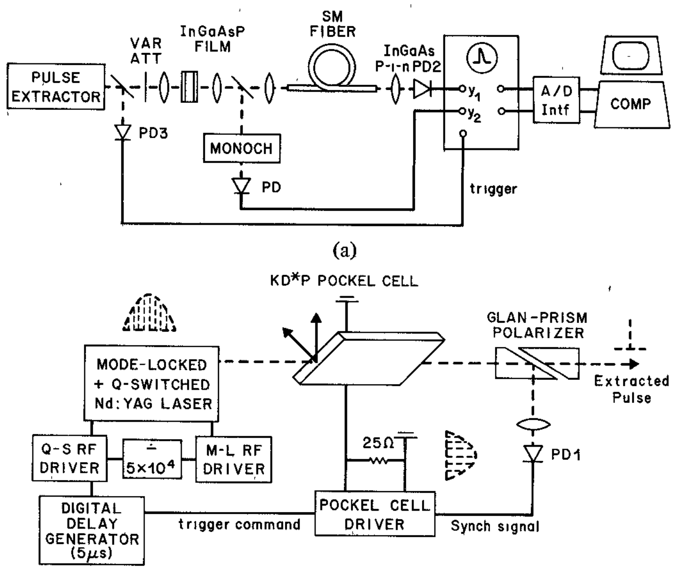

Fig. 1. (a) Experimental arrangement for a thin-film InGaAsP laser transmitter and an InGaAs p-i-n photodiode. (b) Block diagram of a pulse extraction system that is used to select one optical pump pulse from the center of a mode-locked and *Q*-switched train.

I. Introduction

The advent of single-mode fibers with very low loss near the dispersion minimum at about 1.3 μm has prompted the development of semiconductor sources and fast detectors capable of utilizing and measuring the large bandwidth in this portion of the spectrum. The sources have included injection lasers mode-locked in large external cavities [1], [2], or pumped with ultrafast electronic circuitry [3], [4], and ultrashort-cavity optically-pumped whisker and thin-film lasers [5]-[8]. Of these sources, only the ultrashort-cavity optically pumped lasers can be operated at any of a multiplicity of wavelengths [7], [8]. They are tunable, in the sense that a given sample which shows microscopic variations in optical thickness and composition, can produce different output wavelengths depending on the part of the sample which is pumped. It has been demonstrated [7], [8] that with picosecond optical pumping at 615 nm, a set of thin-film or whisker lasers of only six different stoichiometries, including GaAs and $In_{1-x}Ga_xAs_yP_{1-y}$, produced optical pulses in the picosecond range at wavelengths between 0.77 and 1.59 μm with few gaps in the spectrum. Fast detectors, most commonly of InGaAs, have been developed with speeds so fast that detection has heretofore been limited by the time duration of the optical pulse and the electronic detection circuitry [9], [10].

In this paper we demonstrate a high-speed dispersion measurement system utilizing a thin-film ultrashort-cavity laser which is tunable in the range of minimum fiber chromatic dispersion, and an ultrafast, transit-time-limited detector, in which the overall system response is limited by the detector speed and the sampling oscilloscope. The pulse duration of the source is too short to make a measurable contribution to the overall system response time.

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II. Experimental

Fig. 1(a) is a block diagram of the experimental apparatus used to generate and detect short pulses. Optical pump pulses are obtained as follows. An Nd:YAG laser is acoustooptically mode-locked at 100 MHz and synchronously *Q*-switched at 1 KHz in order to generate high peak-power pulses at 1.06 μm wavelength. In order to prevent overheating of the film laser, an optical pulse extractor is used to select a high peak-power pulse once every millisecond and use it to optically pump an InGaAsP-thin-film laser.

The pulse extraction system, detailed in Fig. 1(b), uses a KD*P Pockels electrooptic modulator to rotate the plane of polarization through $\pi/2$ under the command of an electronic control pulse. The output polarizer (GP) is a glanprism which is aligned for extinction when the Pockels cell is not energized. Rejected pulses are reflected onto a photodetector (PD1) and used as synchronizing pulses for the electrooptic modulator. A command signal to gate out a laser pulse occurs when one of the optical synch pulses is coincident with an electrical trigger pulse that is derived from the *Q*-switch electrical drive circuit. The command signal is amplified to form a 5 ns wide 200 V pulse which rotates the output plane of polarization by $\pi/2$ so that a single pulse can be transmitted through the output polarizer.

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Individual mode-locked pulses are extracted from the center of repetitive Q-switched pulse trains. Extracted pulses have amplitudes of 1 kW, about 100 ps duration, and occur with a repetition frequency of 1 kHz. The energy in each pump pulse is large enough to stimulate emission without overheating the film laser. After passing through a variable attenuator [Fig. 1(a)], the pump is focused onto a thin-film laser made of 1 μm thick film of $In_{0.70}Ga_{0.30}As_{0.66}P_{0.34}$ (photoluminescence peak at 1.30 μm) and placed between multilayer dielectric mirrors in an epoxy-bonded structure [5]. The overall cavity thickness is only slightly larger than the film itself. The mirrors have high transmission to the pump. In the 1.2–1.3 μm spectral region, the input mirror has a reflectivity of about 99 percent and the output mirror is about 90 percent. The emergent laser light passes through a pump-blocking filter and is then focused into a 30 m length of single-mode optical fiber.

At the receiver end, light is focused onto an ultrafast detector. The detector consists of an $In_{0.53}Ga_{0.47}As/InP$ p-i-n photodiode (PD2) with a 25 μm active area, mounted in a 50 Ω stripline circuit [9]. The detector response time is estimated to be transit-time limited to about 30 ps. The detector output is then time resolved on a fast optically triggered (PD3) sampling oscilloscope with a 25 ps detector head. The receiver has less than ±2 ps time-base jitter and is able to resolve 45 ps pulse widths. Analog oscilloscope pulses are digitized for immediate processing through an A/D interface and a graphics microcomputer terminal [11].

III. Results and Discussion

Fig. 2 shows a time-resolved output pulse overlaid on a much wider pump pulse which has a half-width of 102 ps. By comparison, the ultrashort-output pulse shown has a measured half-width of 43 ps. The bump after the main pulse appears to be a reflection in the detector mount.

Alternatively, the speed of the received signal can be characterized in the frequency domain by calculating the magnitude of the Fourier transform of an output pulse. The resultant baseband power is plotted versus frequency in Fig. 3 and the bandwidth of the signal pulse is identified by the corresponding half-power frequency. Fig. 3(a) was calculated from the entire output pulse illustrated in Fig. 2 while Fig. 3(b) was calculated after mathematically truncating the electrical reflection attributed to the detector mount. Results show that the received signal bandwidth is 8.4 GHz, but would be increased to 10.5 GHz if electrical reflections were eliminated. By comparison, the bandwidth of the pump signal [Fig. 3(c)] is only 4.9 GHz. These remarkably high bandwidths of the received signal make the InGaAsP-thin-film laser transmitter/InGaAsP p-i-n receiver a very attractive diagnostic system for measuring dispersion and bandwidth properties of single-mode and multimode fibers.

The short pulses illustrated in Fig. 2 were obtained by observing the pulse width on the oscilloscope when the pump amplitude was attenuated (down to about 10 W). Since the pump duration is shorter than the approximately 1 ns recombination lifetime, electron-hole production occurs during the entire pump pulse. As the pump power is reduced, the onset of lasing is delayed. Also, when the pump pulse ends, the laser turns off quickly due to the very short photon lifetime (<1 ps) in the ultrashort cavity. The result is that as the pump power is reduced the output pulse becomes shorter. The measured output pulse is a convolution of the laser pulse, the detector response (estimated transit time limit of 30 ps), and the oscilloscope (detector head, 25 ps response time). When the contribution of the laser is deconvolved it is seen to have a negligible effect and hence is too short to measure in this experiment (<10 ps). The laser wavelength and spectral width were measured using a monochromator with 5 Å resolution.

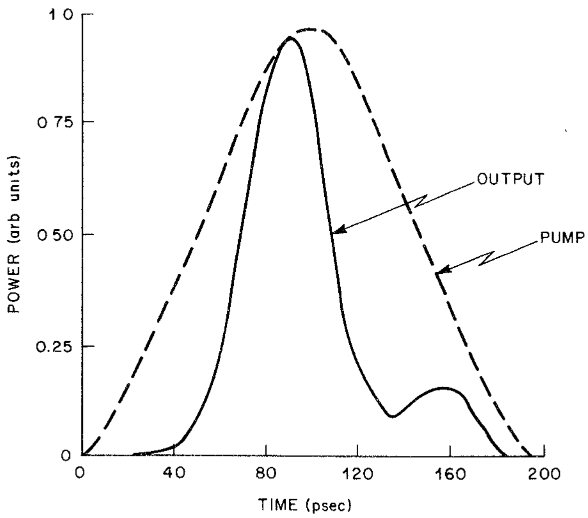

Fig. 2. Optical pulse power versus time. The dashed curve is an optical pump pulse with a 102 ps half-width. It was used to generate the much narrower laser output pulse with a 43 ps half-width.

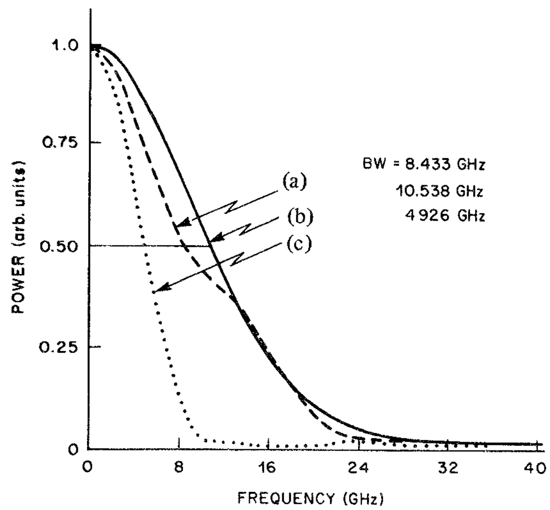

Fig. 3. Baseband frequency responses calculated from temporal pulses in Fig. 2. (a) The measured film laser output pulse. (b) As in (a) except the small reflection bump following the main pulse was mathematically truncated. (c) The measured optical pump pulse.

Fig. 4 shows the tuning range for each of two samples made from pieces of a single thin-film of InGaAsP (crosses and circles), and the photoluminescence spectrum of the film measured with long-pulse duration low-intensity excitation. The laser spectra at a pump power of 30 W peak were obtained by tuning the monochromator to a given wavelength and then

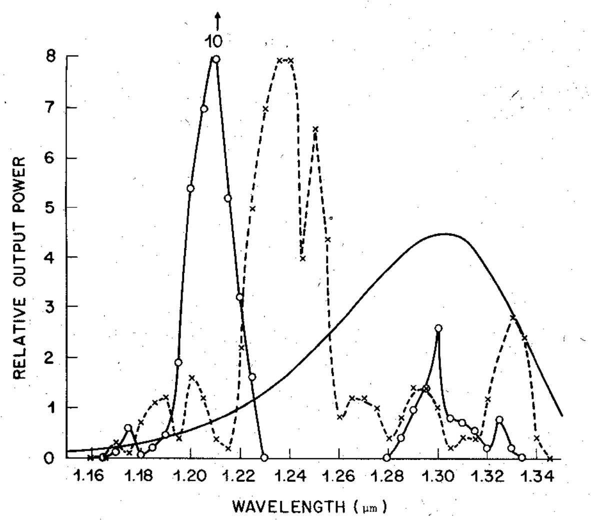

Fig. 4. Relative power versus tuned wavelength for two InGaAsP thin-film lasers pumped as in Fig. 1. Laser linewidth is less than 5 Å. Also shown is the photoluminescence spectrum obtained under low-intensity excitation, solid line.

moving the sample (approximately 250 µm across) transversely in the pump beam to locate the region of strongest output. The maximum output does not occur at the photoluminescence peak but rather at the position of maximum gain due to the combined effects of the photoluminescence and the resonance of the cavity formed by the laser mirrors. Two maxima in the spectra occur for each of the samples. In the shorter wavelength one clearly occurs at a longitudinal resonance since it occurs where the photoluminescence is relatively weak. The longer wavelength output does not occur at a peak of a resonance but occurs near the photoluminescence maximum. The spacing of the resonances $\Delta\lambda$ is given by $\Delta\lambda = \lambda^2/2n\ \Delta t$, where λ is the wavelength, n is the InGaAsP index of refraction, and Δt is the film thickness (assuming a negligible glue-line thickness). For $\lambda = 1.3$ µm, $n = 3.3$, $\Delta t = 1$ µm, and $\Delta\lambda = 0.26$ µm. Thus, if one resonance peak is at 1.20 µm, the nearest ones are at 0.94 and 1.46 µm, both of which are outside the gain curve. The spectral width at any operating wavelength is less than 5 Å. We note that the tuning range is somewhat smaller than was observed for the same material under 1 ps excitation [8]. This is because the much longer pump pulses used in this experiment do not result in as extensive band-filling because competing intraband relaxation processes occur on a picosecond time scale. Nevertheless, a tuning range of 1700 Å is obtained from a single InGaAsP film. In all previous methods [1]-[4] for obtaining short pulses from semiconductor lasers, no tunability has been reported.

IV. Conclusion

In summary, we have demonstrated a measurement system that can resolve optical fiber bandwidths as large as 8.5 GHz. Its essential elements are an Nd:YAG-pumped ultrashort-cavity film laser of InGaAsP with output pulses shorter than 10 ps, with spectral width less than 5 Å (limits of our measurements) tunable over 1700 Å, and a fast detector whose speed is transit-time limited to 30 ps. Furthermore, by substituting semiconductor films of other compositions this system can be used over the wavelength range encompassed by the pump wavelength (1.06 µm) at one end and the wavelengths obtained earlier in InGaAs film lasers (1.59 µm), i.e., the entire range of interest at the present time for optical fiber communication.

Acknowledgment

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J. Stone, photograph and biography not available at the time of publication.

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