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APPLICATIONS OF NONLINEAR OPTIC EFFECTS IN NEW SPECIALTY FIBERS

Reinhard Erdmann

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13. ABSTRACT (Maximum 200 words)

Nonlinear Optic effects are in general higher order processes. This dictates relatively weak interaction coefficients, so that the optical field intensity must be greater in order to observe effects. Optical fiber in particular being amorphous hence centro-symmetric, precludes second order effects, so the ones of interest for this study are already third order (X^3). Fiber possesses, however, some unique properties which greatly enhance the interaction efficiency, and enable practical applications. The small area confinement (typically less than 50 um^2) over very long interaction lengths permits up to three orders of magnitude increase in efficiency over a free space focus. Brillouin scatter is examined even though it is not noticeable with normal sources, because key new applications require ultra narrow line widths, which are shown to bring the threshold to a disturbingly low value of only several mw. Stimulated Raman effects are examined because of their great versatility in frequency shifting for various practical applications. Fiber amplification is shown to enable fiber lasers with very promising properties; extremely short pulses at very low pump powers, fully integrated with only passive components. Interesting follow-on work is indicated in each of these areas.

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Table of Contents

Figures

I. INTRODUCTION

The purpose of this study was to examine how nonlinear optical (NLO) effects can be applied in specialty fibers for optical signal processing. This requires some analysis of how intense optical fields interact with certain materials. The excessive scope of this topic was focussed by the selection of several experiments to explore effective methods of bringing such effects to bear on practical applications. The fundamental reason that this is in general speculative and difficult to justify in normal project work, is simply that the most NLO effects (except near material resonances) are higher order processes with extremely weak interaction coefficients. Furthermore, amorphous optical fiber in general being centro-symmetric, normally precludes even second order effects, so that those of prime concern here are already third order (χ^3)processes. Their effective excitation depends entirely on delivering the requisite high optical field intensity into the interaction volume, or area if one of the spatial dimensions is used for the signal propagation.

There is a very restricted set of parameters that can be optimized. They are: 1) maximum total energy (using a high power laser); 2) spatial compression (focusing beam on small area); 3) temporal compression (concentrating energy in pulses); 4) coherent processes (phase matching to constructively sum the fields); 5) stimulated processes (photon interaction generating a chain reaction of photons which enhance the total process). These methods singly or in combination are utilized in the following experiments. The remaining and very crucial factor is of course the unique collection of each material's properties, which mediate the nonlinear processes and determine which methods can be effectively applied. The attention here has been primarily restricted to single mode (SM) fiber partly because the very small area confinement (50 u^2) of the long interaction length provides orders of magnitude enhancement of the process, and also because fiber is important to applied signal systems. Actually the second experiment included a bulk media application, which effectively illustrated the efficiency problems one encounters even under favorable conditions. Three final selection criteria were applied to these in-house experiments at Rome Lab. Each was required to:

1. Exploit the nonlinear properties of a medium (preferably fiber) which has recently been developed or become available.
2. Contribute publication to active research in that field.
3. Generate results applicable to real optical signal systems.

The last one was the most restrictive, because there are more interesting experiments waiting to be done , than those that may be useful. The content to follow describes what was done and learned in a practical format, and mentions the productive interactions and follow on work which this LDF work helped to define. Also included is a description of each mechanism of operation and how it is utilized. The selected topic coverage is of necessity brief compared with the full range of NLO fiber phenomena.

II. BRILLOUIN SCATTERING

This topic was selected for experimental investigation primarily because in key situations it has a surprisingly low threshold, and in those cases, constitutes the prime limitation to the signal light intensity that can be propagated in SM optical fiber. This is of great significance for many types of fiber systems using high power signal sources for large fan out capability, or for links requiring very high dynamic range operation. A point of interest is that the scattered signal is propagated in the backwards direction, implying that beyond certain threshold levels, nearly the entire signal is back reflected in the fiber. Besides limiting power, this could destabilize or damage the laser source if sufficient optical isolation was not provided. The experimental results here show that in some very useful situations the threshold is fortunately quite high, but that in other important cases it is lower than had been anticipated and limits on the useable optical signal level. To our knowledge at this time, the measurements in this experiment had not been previously performed, possibly because the relatively recent polarization maintaining (PM) fiber and high power ultra narrow linewidth lasers were not readily available. The demands have increased for coherent and high dynamic range optical signal processing, exemplified by some work at Rome Lab, United Technologies Research Center, and NSA. The latter provided some of the specialty fiber for the tests.

Brillouin scatter is an interaction between an incident light wave and a resultant acoustic wave, generated in a non-absorbing medium by the mechanism of electrostriction. Equivalently, an incident photon interacts in the medium with a phonon, resulting in a frequency shifted counter-propagating exiting photon. The phase matching for the process is automatically achieved only in the reverse direction due to momentum conservation with the acoustic wave travelling forward. The medium has a very narrow linewidth about the acoustic resonances and acoustic velocities are very low compared with light. The result is a very small frequency shift with an extremely narrow bandwidth, almost in exact contrast to the properties of Raman scatter described in the next section. In common, however is the automatic phase matching property which allows a scattered signal to build up from noise, interfere constructively with the incident signal, and lead to exponential growth of the scatter signal. This is termed *stimulated* scatter because the increase in light intensity drives the rate equations.

Amplification is a closely related process which takes place if a small signal is injected at precisely the proper shifted frequency in relation to the incident pump frequency. It then experiences exponential growth upon propagation up to the medium's saturation limit. Approximate values of key parameters are:

Brillouin shift: **11 Ghz**

Gain coefficient: $g_B = 5 \times 10^{-11}$ **m/W**

(We note that this is about 2 to 3 orders of magnitude greater than that for Raman, and accounts for the much lower threshold; subject however, to the considerations which follow.)

Brillouin linewidth: $\Delta(v_B)$ = **90 Mhz** (in fiber)

This value shows a considerable broadening compared with bulk silica (17 Mhz @1.55u), mainly due to inhomogeneities in fiber and can even vary somewhat with fiber type.

The overall Brillouin gain in fiber is given by the product of the gain coefficient (g_B) of the fiber material, with the full linewidth of the incident signal integrated with the Brillouin linewidth. The critical implication is that since the Brillouin line multimode lasers having line widths in the Ghz region. Eq 1.

$$g_B = \frac{\Delta v_B}{\Delta v_B + \Delta v_p} g_B(\Delta v_B) \qquad \textbf{(1)}$$

shows how the line width Δv_P much greater than the Brillouin with decreases the gain coefficient. This was proven by our first measurements taking a high power YAG laser at 1.319 u capable of generating over 1.5 Watts (CW or modelocked) and of coupling nearly half of that amount into single mode fiber. Power coupling measurements did not show indications of Brillouin even at this high power.

The result is not surprising and until the recently increasing use of narrow line lasers, such as the distributed feedback diode and the diode pumped Yag ring lasers, the potential problems were not widely noticed. The latter was selected for this work because:

a) Its compact size 2x4x5" made it compact and portable.
b) It was the only laser with the sufficiently high power (100 mw)in a narrow line (4 Khz).

This narrow line allows the Brillouin response to be measured without interference and also permits delta function approximations to reduce the full mathematical integration to a simple expression in terms of measurable parameters. A_{eff} is the effective core area, and L_{eff} refers to the effective length taking loss (α) into account. The factor of 21 is based on the assumption of perfect polarization

$$P_{th} = \frac{21\, A_{eff}\, g_B}{L_{eff}} \qquad (2)$$

$$\text{where} \qquad L_{eff} = \frac{1}{\alpha}\,(1-\exp(-\alpha L)]\,\alpha \qquad (3)$$

overlap[3].

In a real measurement for standard fiber however, the polarization state evolves and becomes uncertain based on length, birefringence, winding and many other factors. The extreme case is random polarization in which case the factor of 21 increases by a full factor of two. This means for one thing that most results reported have an uncertainty in the measured value of threshold by up to a factor of two. This provides additional motivation to include a measurement in polarization maintaining fiber since it provides an unambiguous measurement for correlation for theoretical parameters. The main reason, however, was the fact that in advanced fiber systems and coherent systems, such as some at Rome Lab, many components are in fact polarization sensitive. Almost every fiber based breadboard system includes several polarization "controllers" requiring constant manual adjustment to optimize and avoid loss of signal. This is of course out of the question for many eventual fielded systems, and the use of PM fiber (already available with some components) is a necessary evolution. It is expensive at this stage at upwards of 15K per km.

The experimental goal was to measure threshold in a practical LAN length (1 km) for polarization maintaining fiber. The same length of SM telecommunication fiber was also measured for comparison to reported results[1] on much longer lengths of non PM fiber. The inverse length dependence (Eq. 2) indicates why the lower power levels previously available were adequate for those results.

DESCRIPTION OF EXPERIMENT

The configuration is given in figure 1. The compact laser source is a diode pumped YAG ring laser (Lightwave Technologies) at 1.319u generating 100 mw of optical power, of which 35 mw was launched into fibers. A Faraday isolator was essential to maintain stability and laser protection. Power monitoring was done at the end of the sample fiber and the back scatter was monitored from a beamsplitter in front of the entrance objective. A half-wave plate was later found necessary for the PM fiber measurement to ensure that the polarization could be rotated to a perfect match with the axis of the PM fiber. This was verified by monitoring the maximum output signal. Several iterations were performed on the configuration before settling on the one shown. These initially involved the use of fiber based attenuators and fiber based passive couplers at the entrance and exit ports, but they were later replaced because of difficulty in obtaining closely repeatable results and also to avoid coupling uncertainties due to the mode mismatch of the device pigtails with the sample fiber.

Another major consideration which had not been fully anticipated was the need to eliminate all possibility of lasing. The Brillouin gain is so high when pumped by a narrow line source, that the Fresnel reflection off the cleaved fiber ends is sufficient to generate lasing oscillation even at low pump power. The result is an elevated output signal in both directions leading to a threshold observation which is erroneously low. This also needs to be considered in a real link where signal linearity is important. Both ends must have reflective feedback eliminated.

The method selected for the output end was to cleave the end of the fiber at about 8 degrees, which was somewhat easier said than done. Some others have accomplished this with a custom angled polishing jig. Hoping for something a little more convenient we experimented with hand cleaves by the usual method of following a light scribe with a diamond tool with careful tension and bend. Although no presently made cleavers allow an angle scribe, the Fujukara splicers at Rome Lab have an enlarged monitor screen which enabled the measurement of the angle achieved by a hand cleave to within a degree. It took several attempts to get one right, but coupled tests with a transmitter receiver confirmed high throughput with at least -20db return suppression.

Such techniques are of general utility and partly as a result of this project focus, a Cooperative Research and Development Agreement (CRDA) is in the initial stages of being established with a local fiber optic company (FIS,Inc.) to develop the first commercial adjustable angled cleaver. The suppression at the front end was another problem. An angle cleave could work there but would require focusing in at an angle. Focusing to a 9 micron fiber core is sufficiently demanding completely on axis, so it was opted to use another method. This involved butt coupling the cleaved fiber to the face of a microscope slide with index matching liquid, and focusing the input beam through the opposite face. A straightforward ray trace shows that the remaining reflection from the outer slide face is out of focus for the backwards propagating beam and is attenuated by the fanned out reflection to below 20 db.

DATA ANALYSIS

The final data is shown in figure 1 shows the slope change in reflected Brillouin which indicates the onset of threshold. The magnitude in the PM fiber was about 7 mw input and about 28 mw for SM fiber. Analysis of the data shows that the transmission slope change is much less sensitive to the onset of the threshold condition. It should be emphasized that signal integrity and linearity are adversely affected in a communication system as soon as threshold is reached, even though serious signal loss from backscatter is only encountered with much higher input powers. From comparison to theory[3], a length scaling calculation from 20 meters of SM fiber predicts an approximate 20 mw threshold for SM Fiber. This is in reasonable agreement with the data, considering that the former assumes full polarization overlap which is almost certainly not the case. Any depolarization raises the estimate closer to the measured value with an upper limit of 40 mw. The PM value prediction from equation 2, if one takes A_{eff} as approximately $40u^2$ (from the fiber manufacturer), yields P = 16 mw, with no uncertainty allowed by the theory since polarization is fixed in PM fiber. The fact that the observed value of 7 mw is significantly lower has been communicated to several of the interested users. The question as to which parameter in the theory is in question will be pursued as part of a journal letter.

Other applications could entail use of the narrow gain bandwidth to advantage. The experience of the previous section already illustrated the ease of making a Brillouin laser if any reflections remain at the fiber ends to set up oscillation. A single pass amplifier (as opposed to regenerative types) functions in nearly the identical configuration as the test setup,i.e. no end reflections. A small input signal injected (via a beamsplitter) at the *shifted* frequency would experience exponential gain upon transit through the pumped fiber. The unique feature is that the gain would take place only over the 100 Mhz Brillouin line width forming an optical amplifier with restricted frequency. One of the main unresolved limitations of optical amplifiers is the generation of large spontaneous fluorescence noise which beats with the signal to form broadband noise upon detection. Optical filtering can mitigate the effect at the cost of not utilizing all the gain and requiring additional components with their coupling considerations. These drawbacks are successfully addressed by Brillouin amplification, which could be applied in some narrow band systems.

Another approach to pursue if Brillouin scatter becomes an major problem in short haul systems (<1 km), takes advantage of the fact that the standing acoustic waves are disrupted by modulation to the point of disappearing entirely when a pulsed format below a critical duration is employed. Experiment could determine the best tradeoff of various degrees of modulation for increasing the Brillouin threshold while maintaining minimal effects on the signal. External waveguide modulators using the relatively recent proton exchange method, are now available from United Technologies. These devices demonstrate a 200 mw damage threshold which is a 5 to 10 fold increase over most of the previous types. We have received a sample waveguide for damage threshold tests, and such a modulator could warrant future backscatter reduction tests.

III. RAMAN SCATTERING

The conversion of one frequency to several others is accomplished in Raman scattering by the interaction of the incident light with molecular vibrational energy levels of the medium. The exit light is frequency shifted (up or down) by amounts corresponding to multiples of these energy levels. The resulting side bands are termed Stokes shifts. The effect is nonlinear in that the refractive index is temporally modified by the intensity of the incident beam. The effect is inherently phase matched and so can attain stimulated exponential growth. The practical implications are that just as in Brillouin scatter, no alignment is required. Furthermore, the Raman effect in media such as quartz has a tremendous bandwidth of up to 40 Thz, with the main peak at 13.2 Thz (440cm-1). To summarize, the three main Raman attributes which are seldom consolidated in any other single NLO effect:

1. The shifts in frequency can be extremely large. (eg. In quartz, the higher order shifts take 1.06u to 2u and beyond 3u).
2. The large gain bandwidth can sustain extremely short pulses.
3. The effect is readily excited in many transmissive media, but does require relatively high fields (Megawatts/cm^2).

The selection of the NLO material is the remaining parameter, determining both the magnitude of desired shifts, as well as the critical transparency at the desired shifted frequencies.

The first in-house preliminary work was the observation of Raman scatter in fused silica based fiber, which had been first noted in the network pulse compression project. Fiber contains small dopants of germanium, which can affect the predicted shifts. To asess the level of difficulty in obtaining excitation with availble power and to measure the shift magnitude directly, figure 4 shows the result of coupling about 1 watt at 1319nm into fiber; this is a power intensity of 50 Megawatts/ cm-2 confined to the fiber core. The interaction length of 1.7km was sufficient to make the shifted beam intensity at 1405nm approach that of the remaining pump beam. We also note that an additional line appeared between the pump and Raman lines at some times. This could have been due to four-wave mixing, which would require phase matching for consistent control. Though that is a NLO effect, an application was not clear so it was not included for further investigation at that time.

The ability to generate various frequencies is of very general importance, because at this stage of the technology, available wavelengths (particularly with high pulsed intensity) are still quite restricted. To focus on eventual applications, it was decided to concentrate on one shift of particular practical importance. Several inputs pointed to the need for versatile sources at 1.5u in the lowest loss fiber window, where the main high intensity sources are presently cumbersome cryogenic color center lasers. The fact that YAG lasers at 1.06u (flashlamp or diode pumped) had convenient power to spare, led to the choice of pursuing a first order Raman shift from 1.06u to 1.55u. Besides fiber compatibility, 1.5u is eye safe (as defined by having no transmissive focus on the retina), whereas 1.06u is not. This could be of great importance in laser ranging or free space communications.

A search of the industrial market came revealed that a Raman shifting device was being commercially produced (as a specialty item) based on a pressurized gas cell containing deuterium gas. Examination of one showed it to be very bulky and cumbersome, and requiring pressurization. Spectroscopic data from tables confirmed that deuterium (gas) indeed had an unusually large vibrational transition in the stretching mode, which corresponded to the desired frequency shift. A search of the research literature turned up the interesting result that a group at Bell Labs[2] had diffused deuterium gas into SM telecom fiber by means of a long room temperature exposure. Their pumping experiment, similar to the one previously described, but with a 1.06u laser, indeed yielded the desired shift to 1.56u.

Although a Raman shift experiment had been in the planned tasks, it would only be reported if an in-house experiment could be performed. (Had the deuterium fiber been available, it could have been very interesting.) An informal survey of work at Lincoln Lab resulted in contact with researcher who had worked there on atmospheric Raman scatter, and now had an interest in generating Raman shifts in various liquids. One of them was a deuterium compound dissolved in ethanol. The transmission data showed it to be a promising candidate for the desired shift. An experiment based on this was set up at Rome Lab (Figure 4).

In this effect, a photon given off at the molecular shift frequency, can generate more photons of the same frequency by coherent stimulated emission, hence the term *stimulated Raman*.The efficiency of the process is then driven by the build up in the number of scattered shifted photons. Efficiency is limited by the

Raman gain coefficient : $\mathbf{g_R = 1x\ 10^{-13} m/W}$

A key consideration is the competition between Brillouin and Raman effects. In general, the longer the pulse the greater the probability of the much higher gain Brillouin effect depleting the gain at a lower threshold. Because of its counter propagation it was easy to establish that this did not take place this experiment.

EXPERIMENTAL ANALYSIS

Figure 3 gives the configuration and figures 4(a&b) show the data for conversion efficiency from 1.06u to 1.56u as well as that for the doubled pump line from 532nm to 633nm. The former reached only about 2%, conversion efficiency, whereas the same experiment performed at the YAG laser's doubled output gave about 10% efficiency. The doubled test was actually done first because it was easier to align the lenses and detection systems in visible light. The substantial difference is not accounted for by the predicted direct dependence on wavelength, and indicates that some parameter for the long wavelength result may not be fully optimized. In a focal intensity sensitive application such as this, the interaction overlap geometry is a critical factor. A short focal length has the smallest diffraction limited spot size and highest intensity, but also produces the shorter interaction length from the faster beam divergence. Calculating the optimum values taking into account the medium's non linear response is not staightforward. Several focal lengths were experimentally examined and the best selected for the measurements shown. These issues would not arise in fiber because of its waveguide properties.

A problem of even greater significance was the fact that the full pulse energy available in the Q switched laser (100 mj @ 10 Hz) could not be utilized because of optical flux damage at the outer surface of the fused silica cell windows. Experience with YAG lasers has shown this to be a concern above 30 mj.

$$G = \frac{2gP}{\lambda}\left[\frac{ld^2}{2\pi\lambda f^2}\right] \qquad \textbf{(4)}$$

The expression for the full integrated gain shows a direct dependence on peak power (**P**) when other factors are optimized. Properly matched anti-reflection, as developed for Laser Fusion work and now commercially available, could bring this figure up to about 60 mj. Although the active medium here is not fiber, the contrast in methodology was instructive, and the wavelength generated is ideal for low loss fiber applications.

Another interesting experiment may result due to this work. Lightwave Technologies has developed the first diode pumped - modelocked - regeneratively amplified YAG laser. In following up on a recent visit to Rome Lab, they have expressed an interest in collaborating on a Raman shift experiment using their new laser system. There is no purchase involved. This provides an opportunity for determining the efficiency of the response under ideal conditions which have never previously been available; i.e. very short pulses with high peak power, and a repetition rate in the Mhz range suitable even for optical communications. The key point is that the mode locked pulses are compressed in time by about 10^{-3} compared with the Q switched pulses used in tests to date. this would allow a higher power density (which determines gain), while generating a lower total pulse energy (which determines the cell window damage limit). The data already taken together with these results, would constitute a contribution to be submitted to Applied Optics Letters. In a cooperative interaction such as this, Rome Lab would be able to generate results without doing all of the difficult laser construction.

If the efficiency were improved, this type of phenomenon could become of interest from a device point of view because it is conceivable that a liquid cell for wavelength conversion would be more flexible as an accessory to a YAG laser than presently existing options.

IV. FIBER AMPLIFIERS AND SOURCES

The final topic area involved applications of doped optical fiber. The potential and scope of this topic area quickly grew to warrant additional participation; K. Teegarden and S.Qazi. This enabled faster and more thorough progress, as well as leading to productive follow on work in an increasingly active area.

It should be mentioned that doped fiber, such as Erbium / Silica, involves two distinct media, the host fiber and the dopant material. In the normal applications of Erbium amplifiers and lasers, it is the dopant which plays the active role. In a strict sense amplification and lasing are resonant phenomena, and though they may entail nonlinear response, they are distinctly categorized from non-linear optic phenomena, where the intensity dependent index induces the nonlinearities. A more complicated interplay comes about when the optical field intensity in the fiber medium is sufficient to generate the index nonlinearities in the strict sense. This served as a focus for this last part of the work.

SOLITONS

A nonlinear effect of significance to signal processing is the propagation of optical solitons. This is a true NLO effect and it has been demonstrated with short pulses of proper intensity under the right conditions. A very brief description of the principle for the lowest order soliton illustrates the point. A short pulse inherently entails a spread optical spectrum, and when this propagates in a real medium, the dispersion experienced spreads the pulse in time and degrades its resolution. However, if the pulse's own field intensity can induce the correct nonlinear effect in the medium, then the dispersion effects are precisely compensated and the pulse propagates indefinitely without distortion. Furthermore, pulse durations of pico and femto seconds are naturally generated, and can therefore support extremely high data rates. These soliton effects are the focus of active research for future signal systems including both links or dense local area networks. Though they could be launched into fiber either by an external laser or from within a fiber laser, this work has focused only on the latter.

It is not yet clear whether some future systems would use large numbers of compact soliton sources or whether one high power source could be distributed. It is for this reason that high powered lasers for pumping the fiber (such as Argon+/Ti: Sapphire) were purchased for this project in addition to the much more compact and integrated diode and diode pumped lasers. Besides signal applications, convenient sources of pulses are needed for testing material, component, and system temporal responses.

It turns out that fiber parameters (sign and magnitude of the group velocity dispersion), very strongly favor the 1.5 micron region for soliton work. It is fortuitous that Erbium doped fiber works there as well, and since the lowest propagation losses are also in this region, the future path of fiber based signal systems will most likely concentrate on this wavelength.

The planned schedule could have been loosely summarized by the following sequence. Fiber amplification > CW fiber laser> Pulsed fiber laser> soliton generation in fiber sources, with a time frame of about three months each. Though the sequence has been followed, the work and time involved were underestimated. At this point fiber laser based pulses have been generated, some of which indicate the presence of soliton structure yet to be resolved and controlled. Conference submissions were made on this to CLEO (Baltimore, May 93) and to the Optical Amplifiers and Sources Conference (Japan, July 93).

It should be pointed out that the earlier stages, which may have been conceived as stepping stones, turned out to be of importance in their own right, and warranted the time spent. The main reason for this is fundamental. It will be illustrated that many of desired effects for signals, such as amplification, lasing, and pulse formation could be generated at low pump powers. We have observed here one of the lowest thresholds for the beginning of mode locking in a fiber laser at only about 8 mw pump power. Whenever possible in applications one prefers low power for obvious reasons. Nevertheless, high power capability is almost always desirable or necessary in the initial stages.

For example; one portion of the project was to investigate fiber amplification at 1.3u. This is in its infancy because of material problems in the fiber development, which further serves to illustrate how fortuitous the successful properties of Erbium doped fiber are. We finally were able to obtain a length of the praseodymium doped fiber and found first hand why its physical properties make it impractical at this stage. Not enough has been done with it yet to report on, but one point should be made: To achieve pumping and gain, one generally wants 50 to 100 mw into fiber and twice that from the laser. The only way to obtain that at the required wavelength is by use of a large Ar^+ pumped Ti:Sapphire laser which must be tuned far off its gain peak of 3 watts out to 1.02u where only 200 mw is available. Eventually, diode lasers should attain this as they have for Erbium doped pumping.

FIBER AMPLIFIERS

The following sections include less detail on actual data since summaries of this are in some of the published proceedings based on this work in the references. These devices based on Erbium were very promising at the start, and have continued to be so. Amplification is required in all practical systems and noise advantages are gained by minimizing optical to electrical conversion. A major barrier yet remains in that, while some electronic amplifiers are very inexpensive, almost no commercial optical amplifiers cost less than 10K, and the fiber type are upwards of 20K each. GTE Labs provided the initial lengths of Erbium and Neodymium fiber for research purposes, and this was used here to construct and study fiber amplification. The supplier of any special component was always cited appropriately; and this also aided in obtaining future research samples of this type. In particular a recent publication on dispersive fiber in a delay line[4], incorporated our in-house constructed erbium amplifier for pre-amplification of some of detected signals, which greatly reduced the detector noise.

Even in eventual soliton applications, the distortionless propagation mentioned depends on some loss compensation. This is best done with in line fiber amplification, either erbium doped or Raman pumped. The basic layout of an amplifier is shown in figure 6. After learning the fiber handling and coupling techniques, we were able to achieve up to about 25 db of practical small signal gain.[6] An important feature was the saturation limit at up to hundred mw output, which is orders of magnitude higher than that of the semiconductor type.

FIBER LASERS

The next stage was the construction of fiber lasers using the amplifiers as a gain medium (Figure 7). This turned out to be less of a problem than anticipated. Neodymium(1.06u) and Erbium(1.55u) doped lasers were constructed. Pumping them optically was mainly a coupling issue and a matter of utilizing the best absorption bands. 830nm worked well for Nd (using a Ti:Sapphire) and 980nm for Erbium, which was of prime interest. The 980nm pump laser was purchased from Spectra Diode, and was coupled into fiber with about 50% efficiency, which seems to be about state of the art. Lasertron Corp charges about 4K for fiber pigtailing with that efficiency. It had been thought that applied coatings would be needed on the fiber ends and there was even in-house capability established for applying metal mirror coatings to optics or fibers. Dielectrics on a fiber with partially transparent output coupling would be a more difficult problem. Fortunately, it turned out that:

1. Basic CW lasing with such high gain confinement results from the 4% Fresnel reflections at the cleaved ends.
2. When high reflection for a standing wave cavity was required, a mirror could be successfully butt coupled adjacent to the cleaved fiber, with index matching fluid used if etalon effects remained.
3. The ultimate solution was to utilize a **ring cavity configuration** (figure 7).

In the latter case, no coatings are required at all. The output coupling is obtained from a fused fiber coupler which can be selected for the output coupling ratio desired. The other fiber port recirculates in the gain loop. Though it was known to those working in this field, it was essential to develop effective methods of implementation. The single unidirectional ring laser then became the basis for the work in all the remaining stages. Linewidth and tunability were examined. A laser freely oscillating was not all that stable and would hop between several longitudinal cavity modes. It was found that a very simple intra cavity etalon could lock the laser onto a single cavity mode. This consisted of a thin quartz microscope slide inserted between two fiber beams and collimated by small gradient index lenses. A cascaded tunable version of this was later purchased to permit stable single line output. This could allow wavelength multiplexing while tuning the laser over much of the 40 nm gain bandwidth.

PULSED FIBER LASERS

The main goals for applied signal processing required short pulsed output. Since the lifetime of the excited state in erbium is very long (milliseconds), direct modulation of the gain as in diode lasers is not feasible. Active inter-cavity mode locking with integrated waveguide phase and amplitude modulators was attempted and found to be feasible but lossy. A method was sought which was simple, rugged and required few exotic components. Recent developments in Ti: Sapphire lasers had demonstrated that the laser gain medium could incur nonlinear (Kerr type) effects and function as a passive mode locker as well. Furthermore the pulses so generated were near the transform limits. If such a principle operated in fiber, it could permit mode locking in a simple ring laser with few components. Experimental investigation here revealed that this is indeed almost the case. The only component required was a Faraday isolator to make the cavity unidirectional; a polarization controller (rotator) was desirable to optimize the directional setting of the polarization axis. It should be pointed out that, although the effect was established, much further optimization and control is required.

Some of the initial results were reported at OE Fiber Conference (Boston, Sept 92 Ref.6). It has since been found that a few other groups have also taken such an approach. At this stage we have observed the lowest threshold with the simplest configuration, but the shortest pulses are not yet produced at the higher pump powers desirable for practical signals. The mode locking mechanism is hypothesized to be due a nonlinear induced rotation of the polarization state, and would permit short pulse solitons in a properly matched fiber cavity. Our results are described in reference 7.

It is possible that within a year or so, a method based on this type of approach could become a practical way of producing pico and femto second pulses as well as solitons at 1.5 microns. Regardless of where key breakthroughs come, the experience gained will enable Rome Lab to implement new developments in this rapidly developing field.

V. CONCLUSION

Much productive work has been accomplished in this LDF project. Even though the initial goals were somewhat ambitious and broad, they nevertheless provided an effective focus. In particular, important nonlinear effects in specialty fibers and materials of great current interest were investigated and applied in-house. Productive collaborations were established, and project work of a continuing nature was initiated in areas which warranted it. These would not have been possible without the establishment of this LDF project. There were several indirect spinoffs not previously cited. In particular, a CRDA based on specialty fiber dispersion measurement is now in place with the Corning Research Division. A major part of the initial contact was motivated by this project area, since the erbium doped fiber amplifier was then one of Corning's new product lines. Another potential CRDA is under discussion with Laser Precision Corporation in Utica. This could be based on extending the dynamic range of present OTDR fiber instrumentation by utilizing high power fiber laser pulses.

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3. "Nonlinear Fiber Optics"- Govind P. Agrawal-Academic Press,1989

(References 4 - 8 involved participation of in-house LDF work.)

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6. Optical Communication System Based on a Tunable Doped Fiber Oscillator- K.J.Teegarden,S.Qazi,R.K.Erdmann- Mohawk Valley Conf on Dual Use Applications,Utica NY (May 1992)

7. Self Starting Mode Locked Pulses from a Commercial Erbium Fiber Amplifier- K.J.Teegarden,R.K.Erdmann,S.Qazi, Conf on Optical Amplifiers and Sources- Yokohama,(Japan July 1993)Submitted for publication

8. Self starting Mode Locked Pulses Using a Modular Erbium Fiber Amplifier- R.K.Erdmann,S.T.Johns,K.J.Teegarden,S.Qazi- CLEO(Baltimore 1993)Submitted for publication

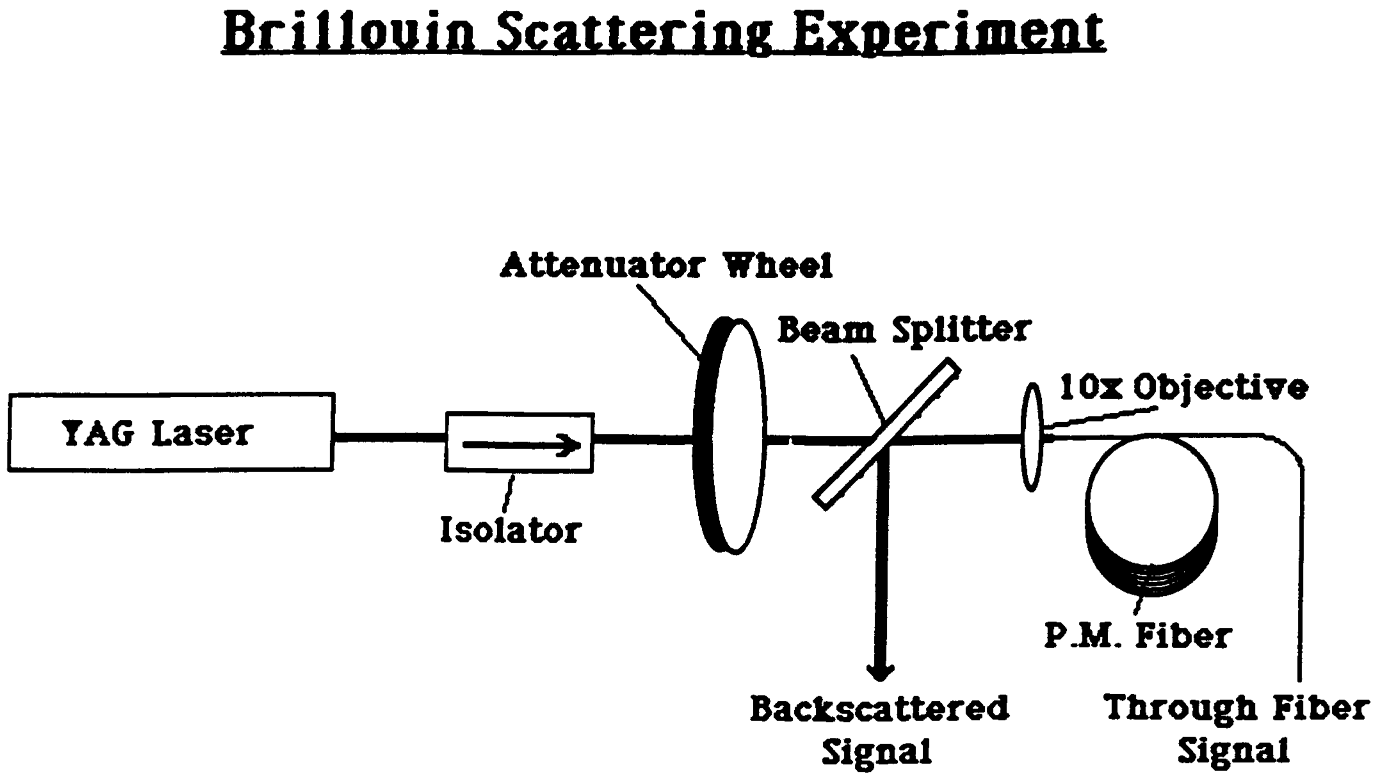

Brillouin Scattering Experiment
Attenuator Wheel
Beam Splitter
10x Objective
YAG Laser
Isolator
P.M. Fiber
Backscattered Signal
Through Fiber Signal

Figure 1:

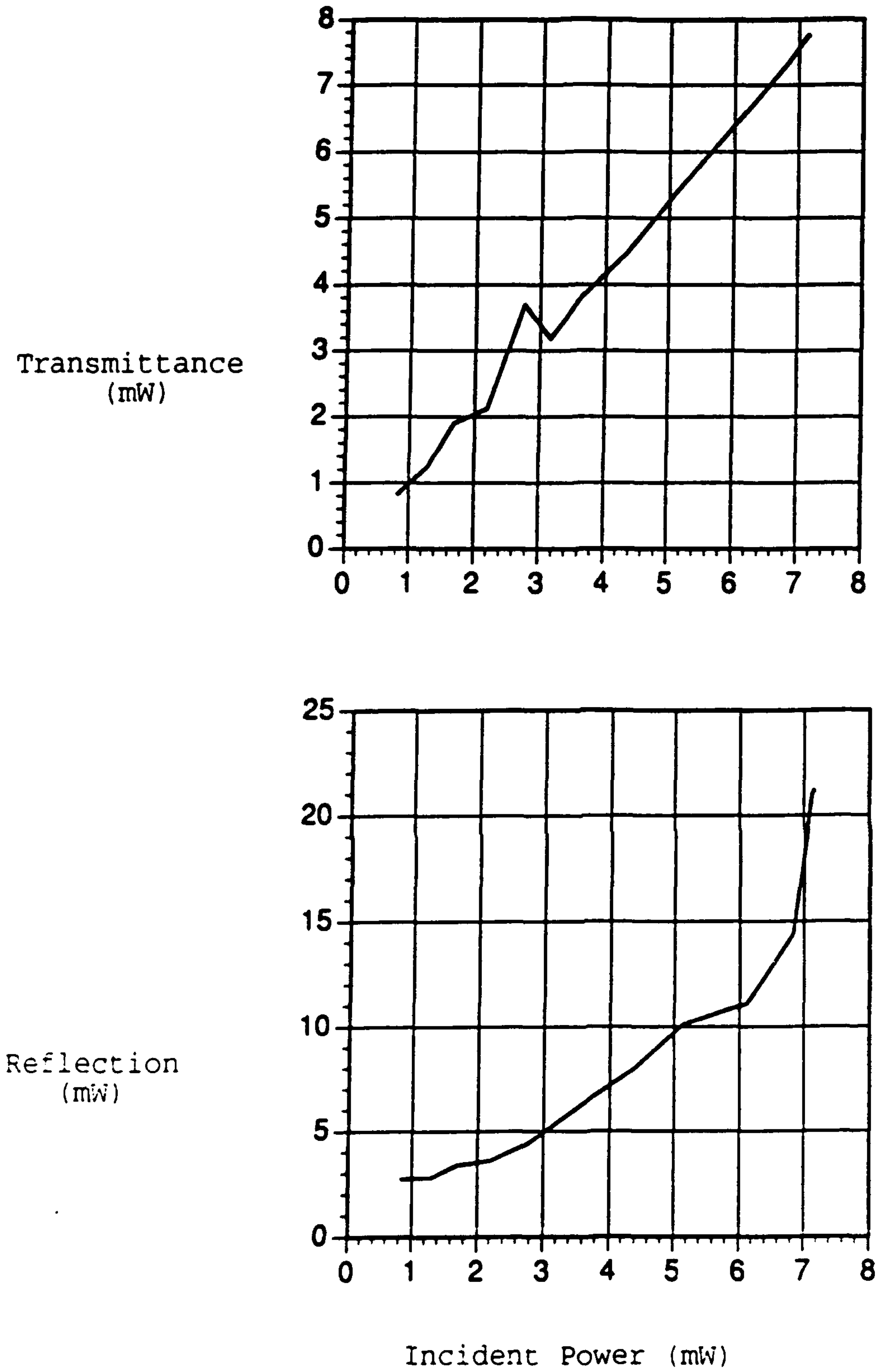


Figure 2a: Brillouin Threshold

POLARIZATION MAINTAINING FIBER (1 Km)

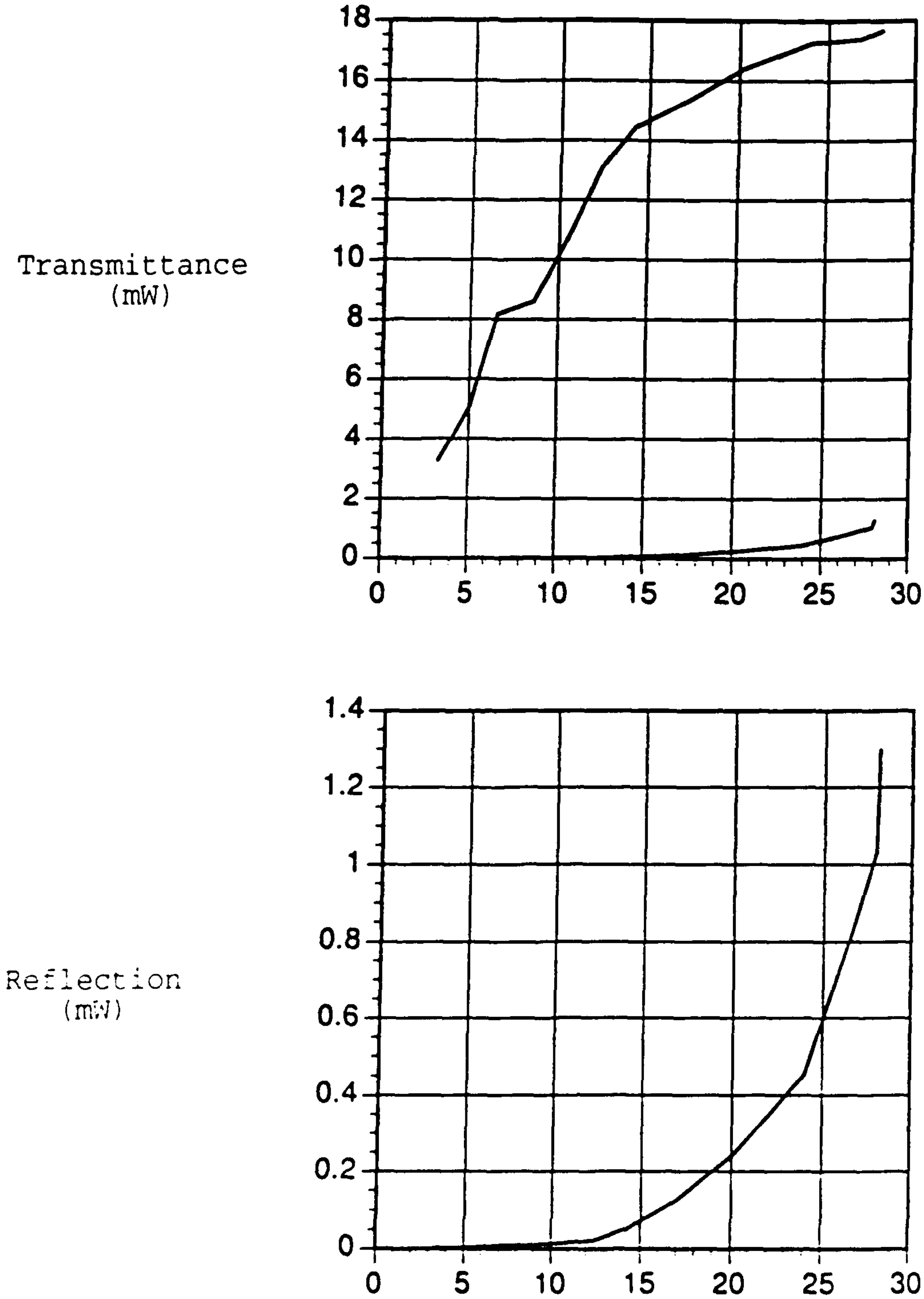
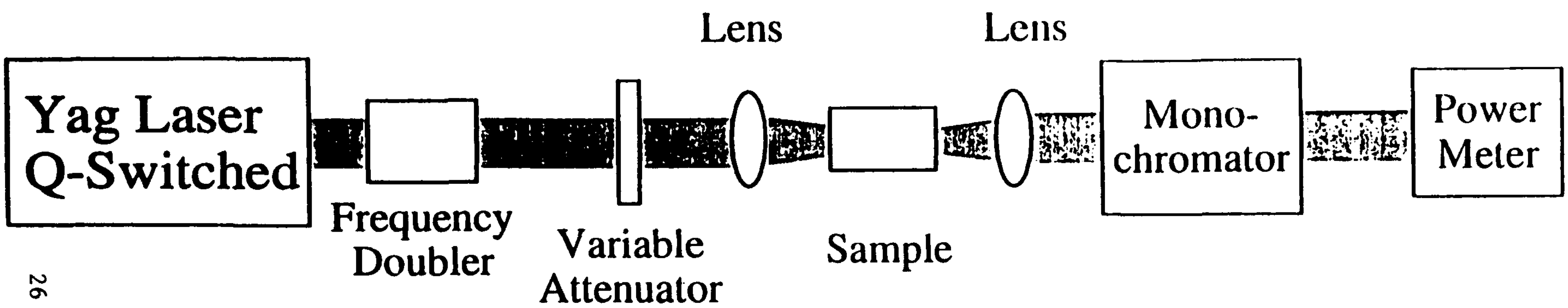


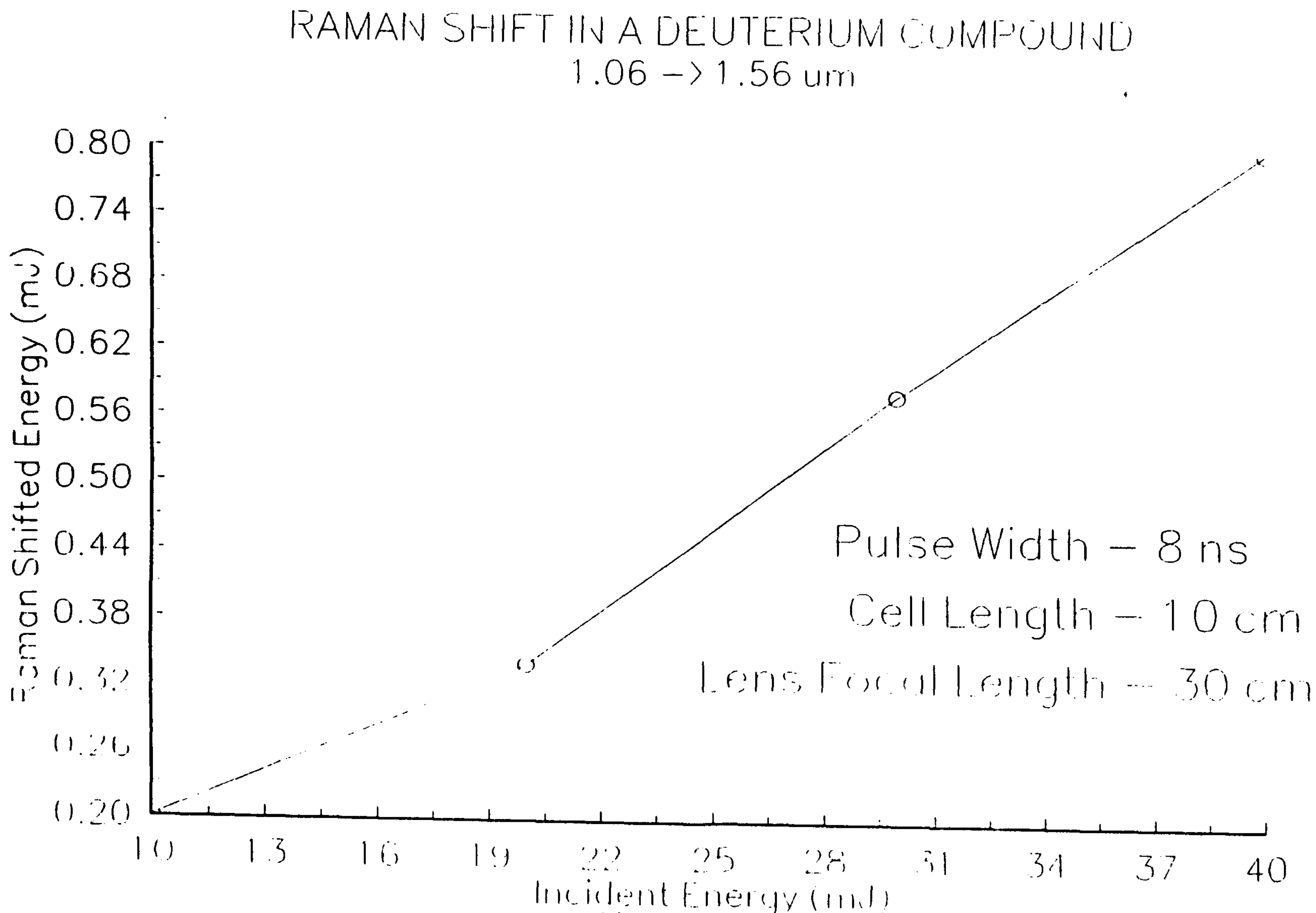
Figure 2b: Brillouin Threshold

SINGLE MODE FIBER (1 Km)



Raman Shift (1.06 to 1.54 μm) Experimental Setup

Figure 3:


RAMAN SHIFT IN A DEUTERIUM COMPOUND
1.06 -> 1.56 um
Raman Shifted Energy (mJ)
0.80
0.74
0.68
0.62
0.56
0.50
0.44
0.38
0.32
0.26
0.20
10
13
16
19
22
25
28
31
34
37
40
Incident Energy (mJ)
Pulse Width – 8 ns
Cell Length – 10 cm
Lens Focal Length – 30 cm
Figure 4a

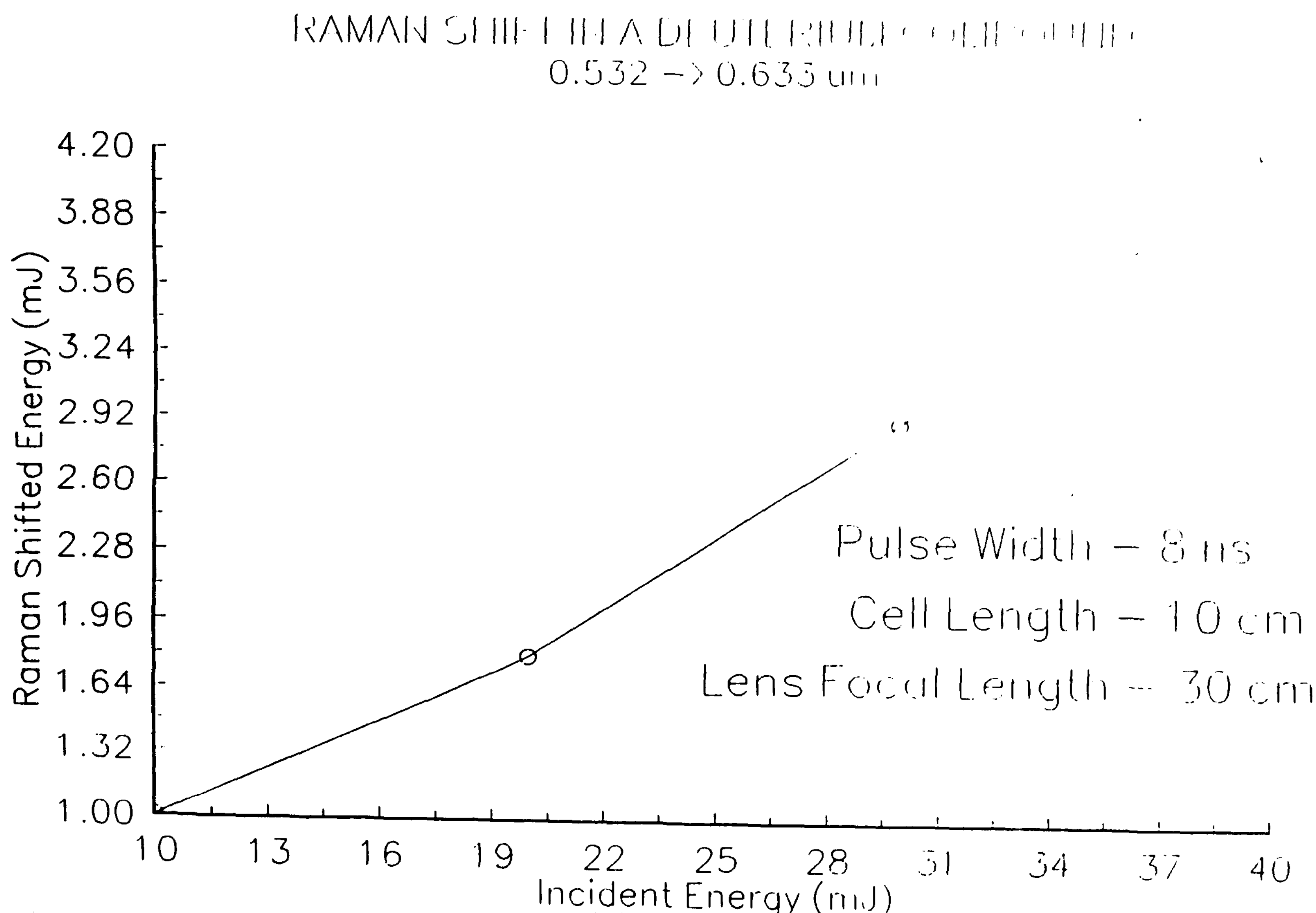
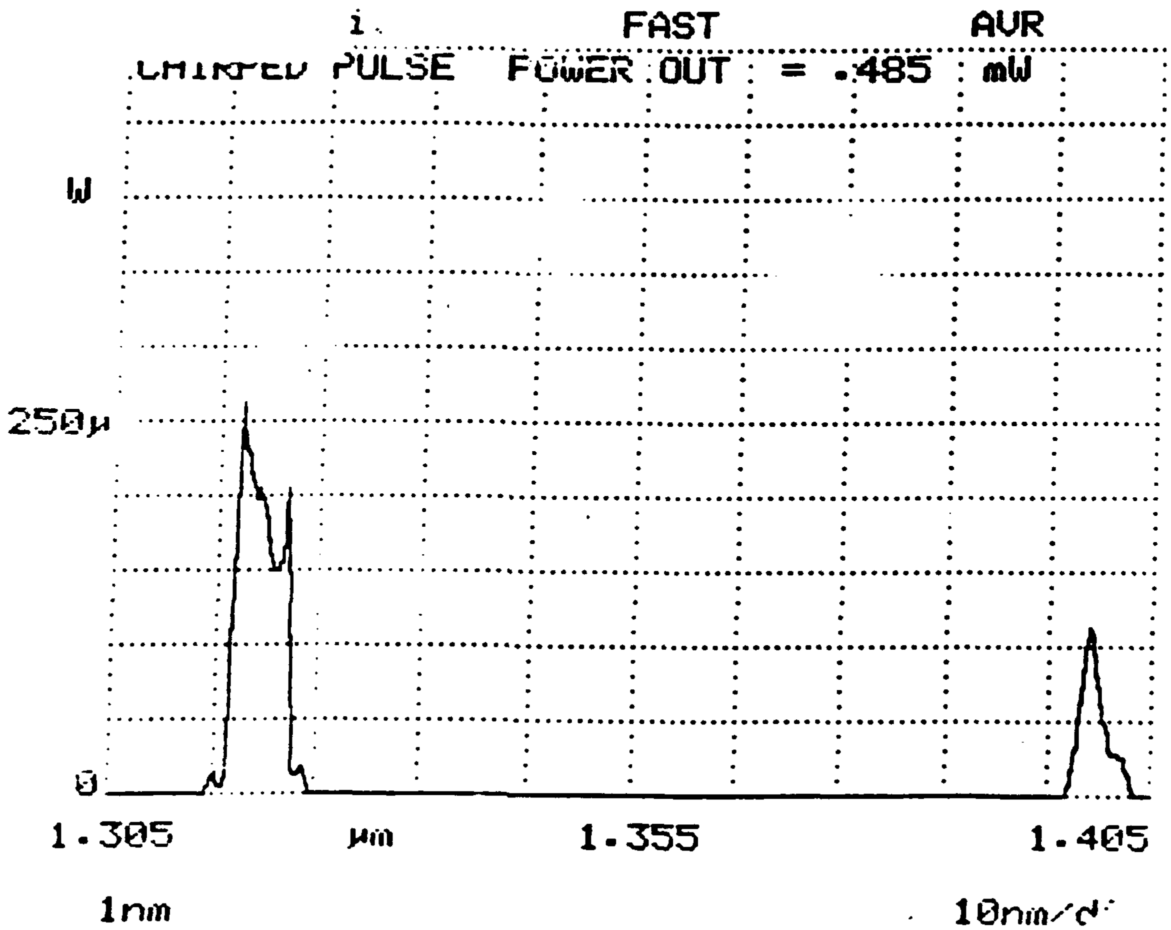

0.532 -> 0.633 um
Raman Shifted Energy (mJ)
4.20
3.88
3.56
3.24
2.92
2.60
2.28
1.96
1.64
1.32
1.00
10
13
16
19
22
25
28
31
34
37
40
Incident Energy (mJ)
Pulse Width – 8 ns
Cell Length – 10 cm
Lens Focal Length – 30 cm

Figure 4b



Stimulated Raman Shift in 1.7 km Dispersion
Shifted Single Mode Fiber

Figure 5:

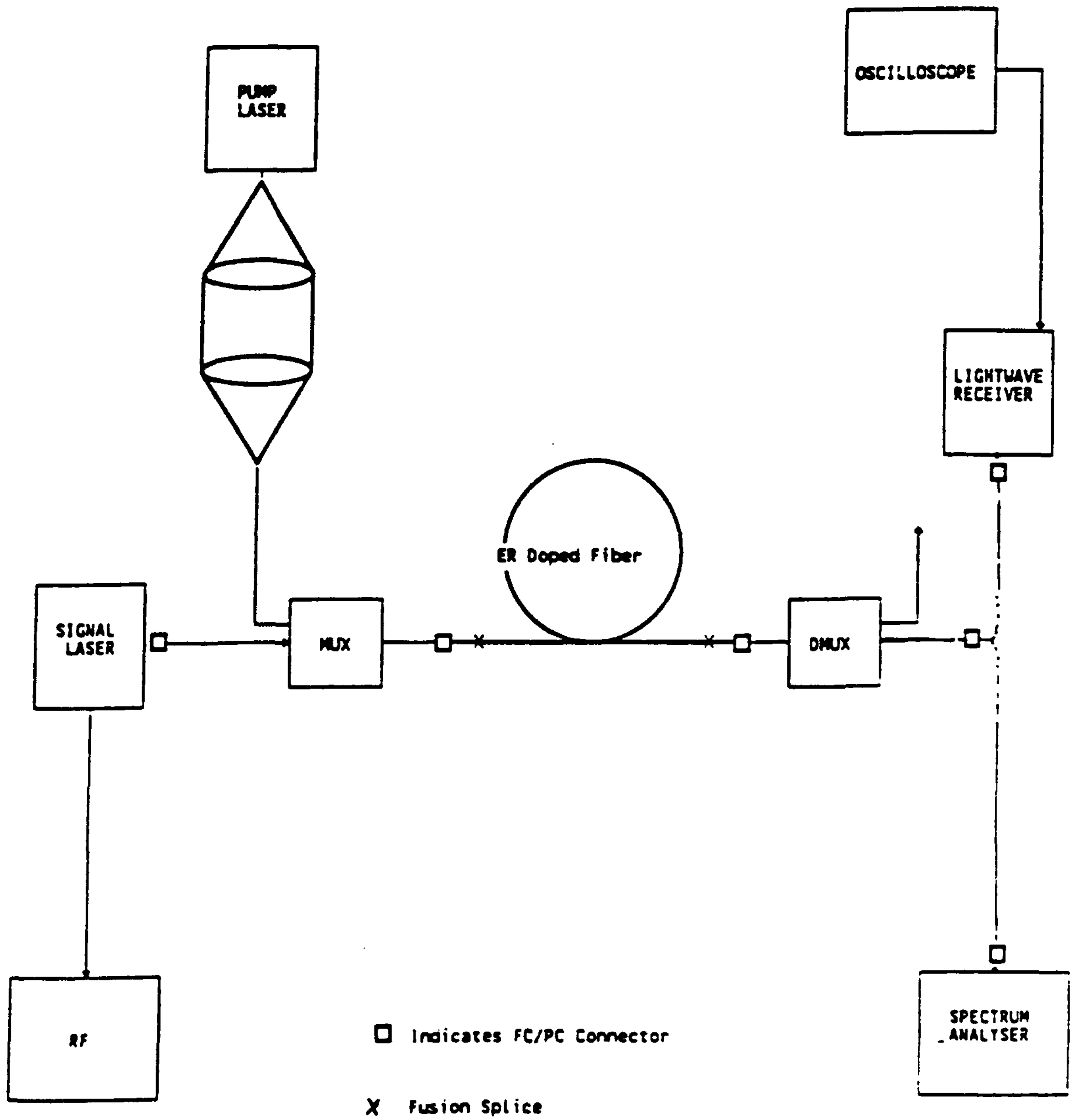
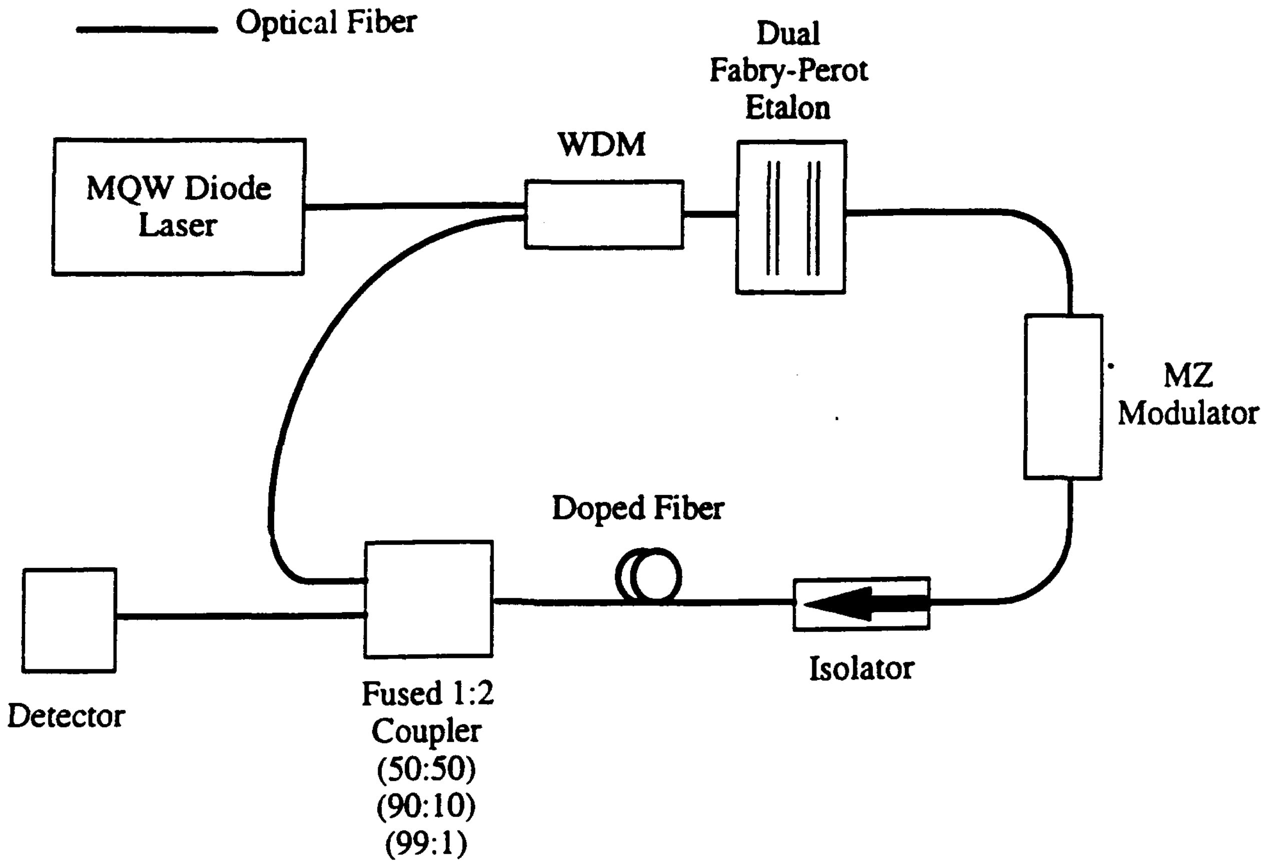


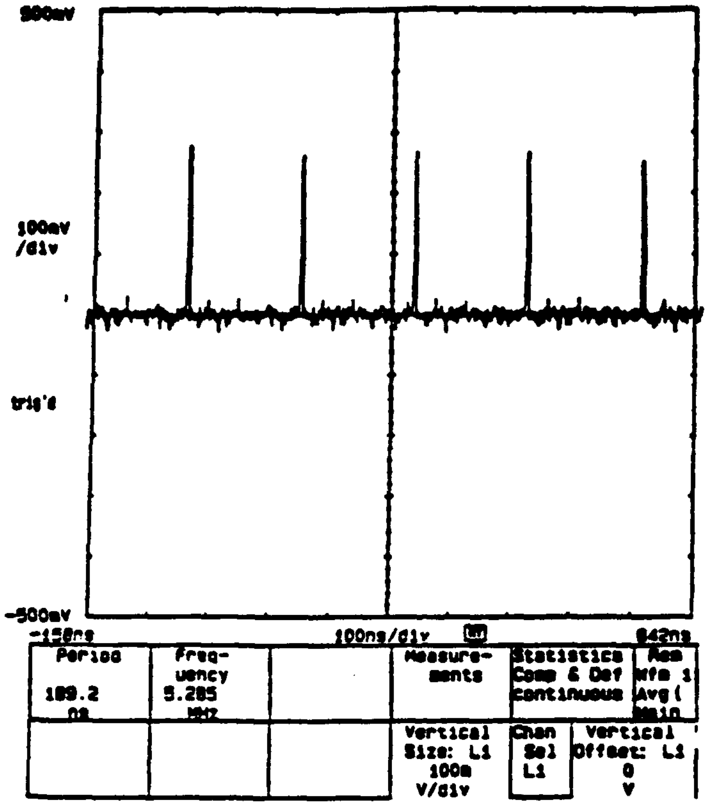
Figure 6:

Experimental setup of erbium doped fiber amplifier system

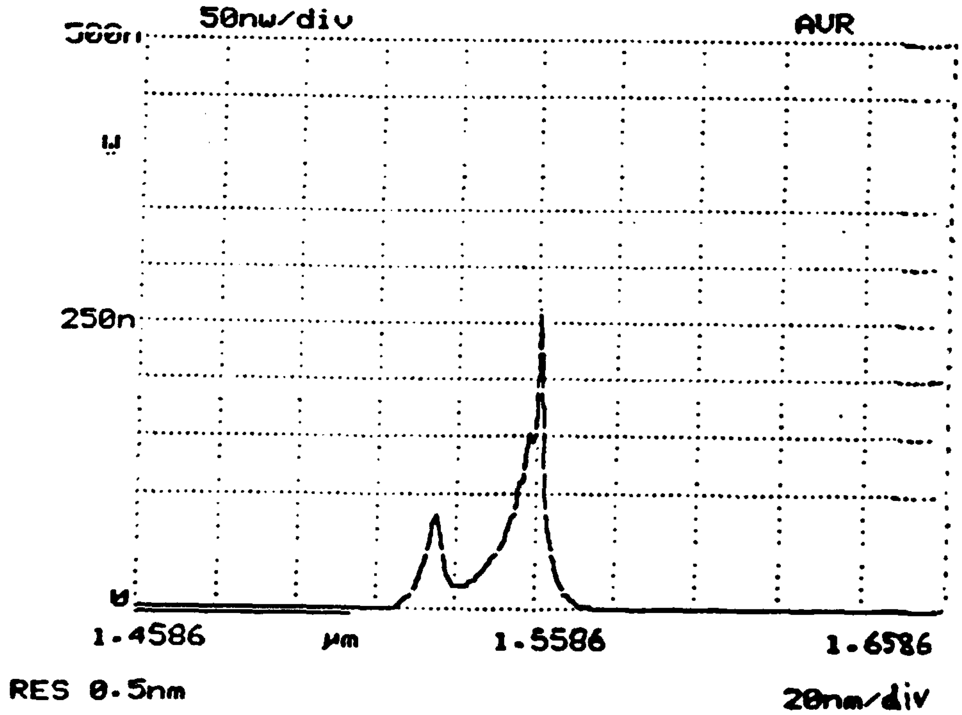


Tunable Fiber Ring Laser

Figure 7:



Erbium Fiber Laser ___ Self- Modelocked Pulse Train



Erbium Fiber Laser ___ Optical Spectrum in Modelocked Operation

Figure 8:

MISSION

OF

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