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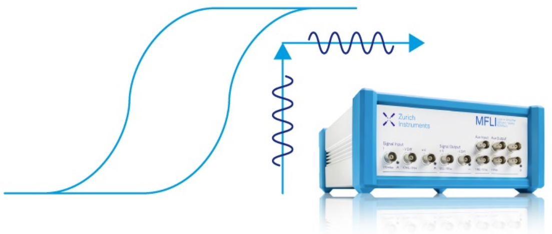
J. A. Armstrong



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MEASUREMENT OF PICOSECOND LASER PULSE WIDTHS

J. A. Armstrong
IBM Watson Research Center
Yorktown Heights, New York
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The special symmetry properties of second-harmonic generation at the surface of a GaAs crystal are used in a technique which measures the shape of the fast pulses from a mode-locked Nd-glass laser. The pulses studied were found to have a full width at half power of between 4 and 6 picoseconds. The technique is capable of measuring pulse widths at least as short as 4×10^{-13} sec.

The achievement of mode locking in Nd-glass[1] and in Nd-YalG[2] lasers is of great interest because of the possibility of producing extremely short light pulses. It is therefore important to make as direct a measurement as possible of the pulse duration. The technique to be described allows one to overcome the bandwidth limitations of optical detection systems and to make time measurements in the picosecond range. For our mode-locked Nd-glass laser we find an upper limit of between 4 and 6 picoseconds for the average pulse width.

The method utilizes the special symmetry properties of second-harmonic generation in reflection at the surface of a GaAs single crystal.[3,4] There are a number of orientations of the polarization of the incident laser light with respect to the crystal axes such that *no* reflected harmonic of a particular polarization is generated. The technique consists in dividing the fast pulse train into two beams of orthogonal polarization, neither of which by itself generates reflected harmonic light polarized parallel to the plane of incidence. If the differential delay in the arrival of the two beams is small enough for the two pulses to overlap at the crystal the net polarization is such that strong reflected harmonic light is generated. One measures the reflected harmonic signal as a function of delay between the two beams. The method is capable of 10^{-13} sec time resolution.

The mode-locked laser is similar to the one described by DeMaria et al.[1] The apparatus for measuring pulse widths is shown in Fig. 1. The laser output is first polarized parallel to the plane of incidence at the GaAs crystal. The light is then divided into two roughly equal beams. One of these (beam 1) is passed through a suitable length of optically active *z*-cut quartz and has its polarization rotated by 90°, making it perpendicular to the plane of incidence. Consequently it cannot interfere with the other beam (beam 2). Beam 1 then passes through a fixed, totally reflecting prism which directs it back to a mirror and second beam splitter. At this beam splitter it is recombined with beam 2, which has traversed a path whose length can be varied by translating a second prism. Thus the use-

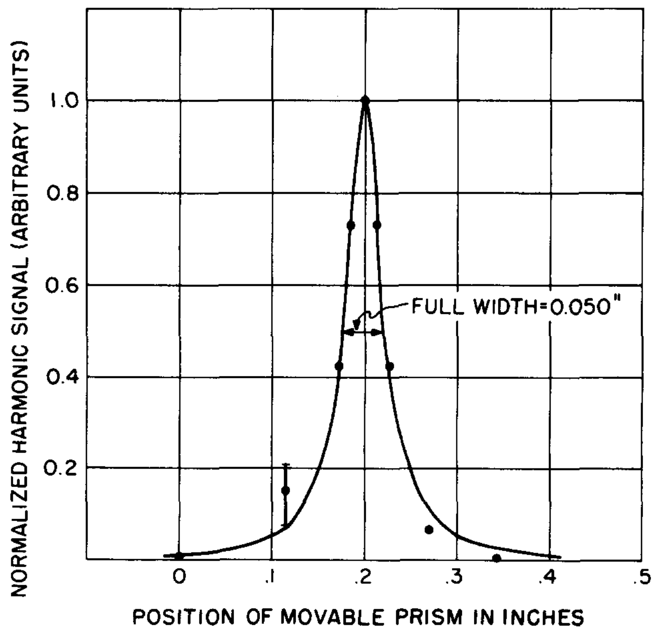

Fig. 1. Apparatus for measuring pulse widths.

ful output of this section of the apparatus consists of two superposed, parallel beams of orthogonal polarization having an adjustable delay between them.

The two beams then fall on the surface of a single crystal of GaAs, which serves to generate second-harmonic light at 0.53 μ. The $[1\bar{1}0]$ direction is normal to the surface and the [001] direction is perpendicular to the plane of incidence (and thus parallel to the polarization of beam 1). The crystal surface was prepared as described in ref. 4. A plane polarizer is located in front of the harmonic detector so that only second-harmonic light polarized parallel to the plane of incidence is recorded. It follows from the symmetry of the nonlinear susceptibility tensor for GaAs that with this orientation of the crystal neither of the linearly polarized beams at 1.06 μ acting alone will generate second harmonic of the required polarization.[3,4] However, when the two beams overlap during their arrival at the sample the resultant polarization of the total laser field during the overlap is approximately in a [111] direction and produces a second-harmonic reflected beam with a large component of parallel polarization. The delay between the beams can be varied in steps as small as 10^{-13} sec if necessary. The curve of harmonic vs delay is the convolution of the fast pulse shape with itself, since a given fast pulse in one beam is always superposed with its mate in the other beam. The harmonic detector has a 5-nsec rise time and thus integrates the fast harmonic pulses. It is found experimentally that the observed harmonic intensity decreases by at least 100 times when either of the 1.06-μ beams is blocked.

Two other detectors serve as monitors. A portion of the original pulse train is used to generate second-harmonic in a fixed piece of z-cut quartz. This harmonic signal is used to normalize the harmonic signal from the GaAs; this is standard procedure in harmonic generation with pulsed lasers. Finally the fast pulses are monitored with a coaxial photocell and Tektronix 519 oscilloscope, whose combined rise time is less than 0.5 nsec. The 519 is used to trigger a dual-beam scope which records the harmonic signals. However, the primary purpose of the 519 is to allow one to reject data obtained when the pulse train from the laser is poorly developed or has weaker secondary pulses interspersed.[1]

An example of the results is shown in Fig. 2. The GaAs harmonic signal has been normalized by dividing it by the quartz harmonic signal. Furthermore, the experimental curve has been normalized to unity at its peak. Note that the signal in the wings is more than 100 times smaller than at the peak. The solid circles are the experimental points and each is the average of at least three laser shots. The solid curve is a Lorentzian with a full width at half-maximum of 0.050 in. The error bar shown is typical for all the points except those in the far wings, where the error is much smaller.

The data fit a Lorentzian quite well, suggesting that the shape of an individual fast pulse is also approximately Lorentzian. This follows since the convolution of a Lorentzian with itself is another Lorentzian. We deduce the full width of the 1.06-μ laser pulses at half-power, Δt, as follows: $\Delta t = 2(0.050)(2.54)/2(3)10^{10} = 4 \times 10^{-12}$ sec. The factor 2 in the numerator reflects the fact that the delay changes twice as fast as the position of the prism; the factor 2 in the denominator comes from the convolution of a Lorentzian with itself. This factor depends, of course, on the precise shape of the fast pulses, and would be $\sqrt{2}$ for a pulse of Gaussian-like shape. For the data of Fig. 2 this would imply a full width of about 6×10^{-12} sec.

We observe the spectrum of the mode-locked laser to be roughly similar to that described in ref. 5. That is, whereas the laser emission with no Q-switching or mode locking is approximately 40-Å wide, operation in the mode-locked regime produces a spectrum over 100-Å wide. In addition, for our laser, we observe an intense central band 5 or 6 Å wide superposed on the broad spectrum (the bleachable dye cell was not oriented parallel to the cavity mirrors, nor at Brewster's angle). This intense central spectrum has just enough bandwidth to support pulses of the duration measured in our experiment. Several interpretations of the spectra are possible. One is that although the bleachable dye couples cavity modes over a 100-Å band-

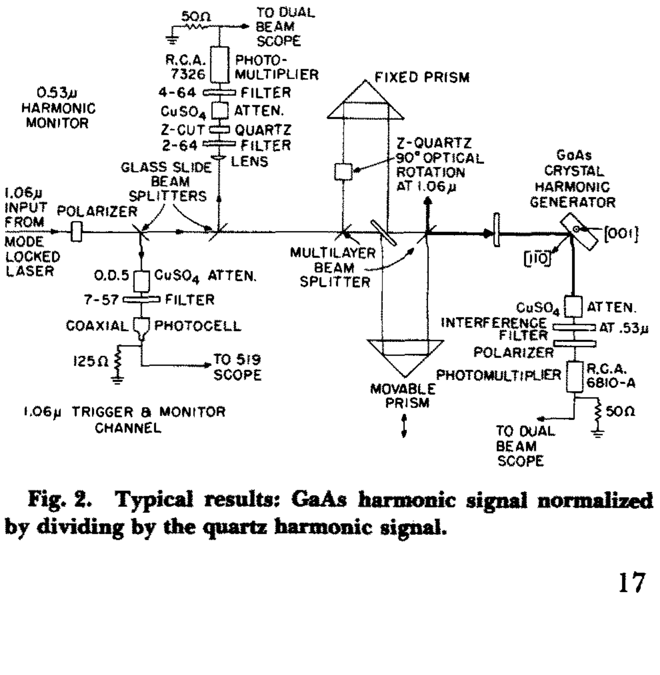

Fig. 2. Typical results: GaAs harmonic signal normalized by dividing by the quartz harmonic signal.

width these modes are not in fact tightly enough coupled to produce 4×10^{-13} sec pulses. Another possibility is that the initial train of fast pulses from our laser (which is the only one used in the harmonic experiments) corresponds to mode locking over a 6-Å bandwidth whereas the later pulse trains are locked over the broader bandwidth. In either case we have determined an upper limit of 4×10^{-12} sec for the pulse width of our mode-locked laser. The technique described, however, should be useful for pulses at least 10 times shorter, and we are attempting to increase the bandwidth of mode-locked operation in our laser so as to observe 4×10^{-13} sec pulses.

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DETECTION OF LIGHT NUCLEI WITH CELLULOSE NITRATE*

W. D. Jones and R. V. Neidigh
Oak Ridge National Laboratory
Oak Ridge, Tennessee
(Received 21 November 1966)

We have shown experimentally that light nuclei, including protons having energies as low as 55 keV, can produce etchable damage in cellulose nitrate. Comparison of our experimental results with theory indicates that the threshold for track registration is about 0.35 MeV per mg-cm^{-2}.

The use of polymers for the detection of charged particles, although a fairly recently developed technique, has been explored extensively for heavy nuclei.[1,2] On the other hand, there is very little information available on track registration in polymers by light nuclei, and we have not found any on proton registration. The object of this Letter is to report the results of an investigation of the energy-loss-rate threshold for track registration of some light nuclei, including protons, in cellulose nitrate.

Track registration means many things to many people. A track formed in the cellulose nitrate by a bombarding nucleus and subsequent treatment by the etchant must be identifiable from the ever present scratches and dirt one finds on the surface. The observer's experience, quality of the optical microscope, and abundance of the tracks all aid in making identification possible. When the energy is so low that the track is reduced in length to almost a dot, single events are not discernible from the rubble; in this case the existence of tracks may be determined only if they are sufficient in number to produce an overall effect. Although little can be learned concerning the particle energy, the general direction of the impinging particle may be determined from such an overall effect. Even this is useful information, however, if one is attempting to determine the existence of a reaction by observing its products, or the location of a reaction by observing the direction taken by its products. Then an acceptable x_{min} can be much less than the 1.5 to 2 μ suggested in ref. 1.

In our investigation of the threshold for track registration in cellulose nitrate, we first calculated the energy loss rate as a function of energy per nucleon by the method of ref. 1. The curve is shown in Fig. 1. Note that it peaks at about 100 kV/nucleon. We investigated track registration with protons from 50 to 550 kV, with deuterons and with alpha particles. The proton results are shown in the photomicrographs of Fig. 2(*a*). Note that the tracks are most easily seen at 550 kV. It should be remembered that for particle energy above the threshold the damage will be etched away and a track recorded, but the length of the track and therefore the ease with which it may be observed increases with energy. It becomes increasingly difficult to detect the direction of the particle as the energy is

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