

Technical Notes

The following five Technical Notes have been contributed by authors at the Bell Telephone Laboratories, Inc., Holmdel, NJ 07733. Other contributions of a comparable nature will be welcomed for Journal publication.—Ed.

Photographic and Photoelectric Detection of Optical Pulse Codes

By J. S. COURTNEY-PRATT and L. E. HARGROVE

In 1965, we studied the light output of an intracavity-modulated gas maser using photographic and photoelectric techniques. The description of the work has been published in *Jour. SMPTE*, 74: 1085-1095, Dec. 1965. We found that we could easily photograph the individual pulses of light even when there was optical attenuation (from the output end of the maser to the photographic emulsion) of about a factor of 1500. With this attenuation, the photographic dots were still quite detectable, i.e., the signal/noise ratio was still reasonably large.

At another time during the experiments, we allowed the light from the maser to fall on one of the new fast photocells that had been developed at Bell Telephone Laboratories. The output from the photocell was displayed using a sampling oscilloscope. The pulses are well above noise. The peak pulse height was perhaps 10 or 15 times the rms value of the noise. This meant that we were much more easily able to detect the pulses photographically than photoelectrically.

In our work, photographing the glints from the mirrors on Telstar (see the paper by Courtney-Pratt, Hett and McLaughlin, *Jour. SMPTE*, 72: 462-484, June 1963), we found that it was considerably easier to detect the pulses photoelectrically than it was to detect them photographically. The glints from the mirrors on Telstar have a duration of about a millisecond, whereas the pulse duration from the intracavity-modulated maser is about a million times shorter.

Why is it that in one set of experiments (Telstar glints) it was easier to distinguish a light pulse using a photocell while in the other set of experiments (the maser experiments) it seemed easier to detect the pulses using photographic recording? It seems that the reasons might very well be quite general and be dependent on the time scale. To detect very brief pulses at high pulse rates, the bandwidth of the photocell must be large. Some forms of noise in the amplifier associated with the photocell would increase either as the square root of the bandwidth or perhaps even directly as the bandwidth depending on the origin of the noise.

Suppose, on the other hand, we know just where on the photographic emulsion a patch of light may fall or may not fall. We can consider the photographic density with or without the light, and we should consider what change in density the light produces relative to the statistical fluctuations in density that occur in correspondingly sized patches of the emulsion where it is otherwise unexposed. If there is no reciprocity failure in the emulsion, the signal should be just as detectable whether it is recorded at high speed or not, as the noise associated with the fluctuations in photographic density is unaffected.

Consider a communication channel in which one modulates the intensity of the maser beam. For simplicity, consider on-off modulation or pulse code modulation with a pulse duration t (or a little less) and a pulse repetition frequency $1/t$. If $1/t$ is small (say less than a million cycles per second) it would probably be much easier to detect the pulse code using a photo-multiplier as the detector. Suppose, however, we wish to increase $1/t$ to 10^9 or even higher. It then seems that it is difficult to obtain a photocell in which the noise is low enough that we could use small signals. Photographic detection would appear relatively better. We could take out the advantage in several

ways: perhaps we could use a smaller transmitter; perhaps transmit over greater distances, or under more adverse conditions; or perhaps could distinguish more levels of signal than the simple on and off. There would be the delay in processing the film, but rapid processors can operate in a matter of a second or two. Readout could be at full speed because local readout source intensity could be as high as one wished. Alternatively, if one wished to have considerably easier readout systems, one could readout at some lower frequency. Alternatively, with pulse sequence multiplexing, one could use different photocells (one for each multiplex channel), and divert the readout signal after its passage through the recorded sequence on the film to the appropriate photocells.

Multiple Images

By J. S. COURTNEY-PRATT

Some time ago, I was asked to consider ways of producing multiple images of the kinds required in microcircuits and semiconductor work. One could make use of the multiple reflections between two (partially transmitting) reflectors spaced a short distance apart to produce a string of images. The quality of these images would be dependent only on the quality of the reflecting surfaces and so could be high. The intensity drops off from one to the next by a small factor, but the drop could be as small as a few per cent and perhaps even less, and in any case could be compensated if one wished by use of a tapered or stepped wedge at a later point in the system. One could use each of these reflected images as a source for a second set strung out in a different direction, probably at right angles to the first set, or perhaps at 60° . One would then achieve a two-dimensional array of images. The intensity in the absence of a correcting mask would vary a little from one image to the next. On the other hand, the image quality could be high and the optical components required would not be critically difficult to manufacture.

Increase of Flux Per Unit Area by Refraction From a Plane Surface

By J. S. COURTNEY-PRATT

Some time ago, I was making calculations on the amount of light that is reflected and refracted at a surface near the critical angle for total internal reflection. To check a point, I began to read Section 28 of the book *Fundamentals of Optics*, 2nd. Ed., by F. A. Jenkins and H. E. White (McGraw Hill Book Co., 1950). I noticed particularly the following paragraph on page 564: "It is the total energy of the reflected and refracted rays that is complementary. Now the energy of the beam of light with constant amplitude depends on the index of refraction of a medium as well as on the square of the amplitude. It also depends on the area of the beam, and, as was shown in Section 2.1, the cross-sectional area of the refracted beam increases with the angle of incidence by the amount $\cos \Phi' / \cos \Phi$."

Jenkins and White have commented that the beam gets larger when it is refracted obliquely into a more dense medium.

I had been considering a beam of light that was incident on the bounding surface from the more dense side. I had been drawing curves of the amount of energy that would be refracted out of the dense medium as a function of the angle of incidence. I checked again the angles of incidence and refraction for that angle that would give an energy in the reflected beam of 75% and therefore an energy in the refracted beam of 25% of the incident energy. I realized that the width

of the refracted beam (as we were moving in the opposite direction to that considered by Jenkins and White) would be considerably smaller than the width of the incident beam. In fact, for the case considered, the reduction in the width of the beam would be by a factor of about 20. The brightness of the refracted beam would therefore be greater than that of the incident beam — a rather unexpected result. If we define here the brightness as the energy per unit cross section, or as the flux per unit cross section, then the increase would be about five times. There is nothing in this that contradicts the second law of thermodynamics as the divergence of the brighter refracted beam will be greater than the divergence of the incident beam.

I asked R. P. Chambers to calculate the gain in brightness for various angles of incidence. He computed the ratios of the cross-sectional areas of the incident and refracted beams, L/W , and had the computer plot this against the fraction of energy, $1-Y$, that is refracted out from the dense medium. A graph has also been computed for the flux per unit area of the refracted beam relative to the flux per unit area of the incident beam, $(1-Y)(L/W)$ versus $1-Y$. Brightness gains of a factor of 6 or more are quite possible. These curves have been computed for one value of refractive index, ($\mu = 1.6$), and we have chosen that plane of polarization of plane polarized light that gives the greatest effect.

While these computations were being made, I talked about the general principles with L. E. Hargrove and with E. Eisner. L. E. Hargrove suggested that one might use two such devices in planes at right angles to one another. One could then obtain a gain in brightness of up to 40 times (for maximum effect, one might need to add also some component that would appropriately rotate the plane of polarization before allowing the beam to enter the second device).

Hargrove and Eisner and I went to our laboratory and put a prism in the path of the beam of light from a helium neon gas maser. We could, quite easily, see that one could obtain an increase in brightness when the angle of incidence was just less than the critical angle for total internal reflection. As the refracted beams diverged more than the incident beam, we found that the image was only detectably brighter at positions close to the point of emergence from the prism.

Similar increases in flux per unit area could of course be obtained using convergent lens systems. The novelty of the idea resides in the fact that here this has been done by the use of plane surfaces only. There could be cases in various branches of optics, perhaps in spectrography, where this new system might be an advantage.

Later experiments by H. M. Janus, while a temporary employee at Bell Telephone Laboratories (under the provisions of the IAESTE Program), showed a brightness gain of three times with a single prism near the plate of a spectrograph, and an overall gain of eight times using two prisms working in the same plane in series.

Pulse Extraction From Masers

By J. S. COURTNEY-PRATT and L. E. HARGROVE

We have considered a question concerning the energy in a pulse of light in an intracavity-modulated gas laser. If, for example, the transmission coefficient of one of the end reflectors is one per cent, then the energy in the pulse inside the maser is about 100 times the energy of any one pulse emitted through the end reflector. Hargrove suggested that it was possible to extract the pulse from his intracavity-modulated gas maser, by any one of a number of means, and use the pulse so extracted for photography or for other purposes.

A convenient method of extracting such an internal pulse might be by means of a rotating glass prism which at some instant will have turned to such an angle that the pulse of light inside the maser will no longer suffer total internal re-

flexion. The prism could well be a Porro prism or other retro-reflecting design and could act as one of the end reflectors of the maser. This arrangement has the advantage that the prism can act as a good retroreflector for some significant and sharply bounded range of rotation (say 15 degrees). During rotation through this angle, the intracavity maser pulse would have time to build up to full strength. As soon as the prism passes the critical angle, the transmission rises suddenly (over a rotation of say one-hundredth of a degree). The device thus can allow the relatively slow buildup of a high energy pulse followed by the rapid extraction of this pulse. The process could repeat on the next rotation of the prism, or could easily be suppressed if desired as the repetition rate (which equals the rotation rate of the prism) could be low enough even for use of a mechanical shutter.

Typically, if the prism rotates at say 2,000 revolutions per second, the time between pulses would be 0.5 milliseconds, the time for buildup of the pulse in the maser would be about 20 microseconds, and the time for switching to extraction of the pulse would be about 10^{-8} seconds.

This general principle of extraction of energy from inside the maser is not restricted to gas masers, and is not restricted to "continuously" operating masers. In fact, there could be useful applications of this principle in most other kinds of masers. For example, consider a naturally occurring spike in a small ruby maser. The energy that is transmitted through a partially reflecting end mirror associated with this spike will be much lower than the energy within the ruby maser associated with this spike. It would probably be useful on occasion to insert inside the ruby maser cavity some device which could be switched so that the energy within the maser could be extracted. In a typical case, one might then get a spike out which was 20 times as large as that ordinarily available from the small ruby maser. The gain would be largest in those masers that have high reflection and low transmission end coatings, but might be significant even in other masers that have relatively low reflection coefficient reflectors. One could make use of the idea in ordinary pulse-operated masers as described, or (with some greater attention to the timing) in Q-switched masers. The duration of the pulse so extracted will not be longer than the time for light to travel twice the length of the maser, but the peak power will be high.

Multiple Level Recording — Maps, Plans, Etc.

By J. S. COURTNEY-PRATT, R. P. CHAMBERS
and H. M. JANUS*

We have been interested for some time in unconventional methods of storing information on photographic films. C. Wyckoff, who works with Edgerton, Germeshausen & Grier, Inc., developed some years ago a triple layer film called XR film. The three emulsion layers in this XR film had different sensitivities chosen so that one layer would record very faint signals, the next layer would record medium brightness levels and the third layer would respond only to very intense light levels. The characteristics of the three layers were so chosen and adjusted that the total latitude of the film was the sum of the latitudes of the three layers considered independently. This film could record signals that were different in illumination level by a factor of $10^3:1$, or even more.

We think that composite emulsion layers could be assembled following different criteria to make up film that would be useful in other respects. These ideas were stimulated by consideration of the XR film, but are different in that the products we suggest are not formed as the assembly of emulsions chosen to increase the latitude of the composite film, but are chosen

* At the time this work was done, temporarily at Bell Telephone Laboratories.