Optical Correlation Technique*

This communication describes an optical technique for correlating electronic signals in real time. By this technique 0.5-μsec pulses of 15-Mc carrier were dispersed to 60 μsec and compressed back to 0.5 μsec using linear and pseudo-random frequency modulation. The correlation was accomplished with two identical optical systems, one serving as a transmitter and the other as a receiver. Correlation was also obtained in a single optical system having both transmit and receive capability.

The experimental arrangement is shown schematically in Fig. 1. The operation is as follows: Light from a slit source is collimated by lens L_1 onto an ultrasonic light modulator (ULM). The slit source was produced by focusing the light from a 100-watt mercury arc on a slit. The ULM consists of a small light-transparent tank of water with a quartz transducer mounted at one end. Within the tank and adjacent to the propagation path of the transducer is located a film replica containing a series of lines of varying periodicity similar to a nonuniform diffraction grating.

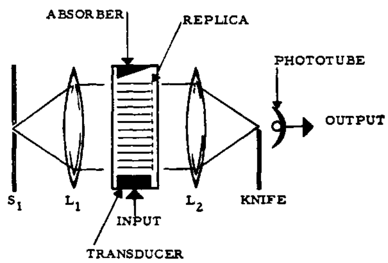

Fig. 1—Optical correlator.

When the transducer is excited by the 0.5-μsec pulse of 15 Mc, it sets up ultrasonic waves in the water which modulate the wavefront of the collimated light and scan the replica. The ultrasonic waves disturb the water in only a narrow region compared to the length of the replica (about 1/120 of effective length). Since the line spacing in the replica corresponds to the ultrasonic wavelengths in the water, the moving ultrasonic "grating" in effect beats with the replica lines and causes fluctuations in the intensity of the diffracted light focused on the photomultiplier tube by lens L_2. The knife in front of the phototube serves to remove the noninformation-carrying components of the light. The variation in the spacing of the replica lines (linear or pseudo-random) corresponds to the signal bandwidth of 2 Mc. Hence, the frequencies contained in the 0.5-μsec pulse are selectively delayed over 60 μsec, the time required for the ultrasonic waves to scan the replica. The output of the phototube is a 60-μsec electronic pulse having a 2-Mc bandwidth about 15 Mc.

For compression, the dispersed pulse, suitably amplified, is applied to the transducer in another identical optical system or, in the case of single system operation, to a second transducer in the same ULM (used for generating the dispersed pulse). This time, however, the replica is scanned in the opposite direction to reverse the frequency delay contained in the dispersed pulse. Correlation occurs when the ultrasonic waves match the replica over the entire aperture. The phototube output at correlation resembles the initial 0.5-μsec pulse and contains the 15-Mc carrier.

Fig. 2 shows the dispersed pulse and Fig. 3, the compressed pulse obtained with linear frequency modulation. Tapering of the dispersed pulse is attributable to transducer and amplifier band-pass characteristics. The sharp cutoff at edges of the dispersed pulse correspond to the optical system aperture limits.

Fig. 4 shows the dispersed pulse and Fig. 5, the compressed pulse obtained with pseudo-random frequency modulation. No tapering of the dispersed pulse is observed since the frequencies are randomly distributed. Amplitude variation within this pulse is caused mostly by imperfections in the film replica. The replicas used in the experiments were produced by a special photographic technique developed by the writer.

Fig. 2—Dispersed pulse with linear modulation (10 μsec/box).

Fig. 3—Compressed pulse with linear modulation (2 μsec/box).

Fig. 4—Dispersed pulse with pseudo-random modulation (10 μsec/box).

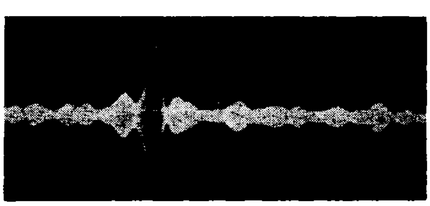

Fig. 5—Compressed pulse with pseudo-random modulation (2 μsec/box).

Earlier work by Reich and Slobodin[1] discussed real-time optical correlation by a Schlieren technique involving the use of four lenses. The lenses were required to be of very high quality to produce acceptable correlation. In the present system, only the collimating lens need be of high quality; the second lens merely serves to integrate the light onto the phototube. Moreover, positioning the replica adjacent to the acoustic beam path eliminates signal degradation caused by lens field curvature and makes optical alignment much less critical.

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[1] A. Reich and L. Slobodin, "Optical Pulse Expansion/Compression," presented at 1961 Natl. Aerospace Electronics Conf., Dayton, Ohio; May 8, 1961.

A Proposed Class of Heterojunction Injection Lasers*

Laser action in semiconductors has so far been reported only for direct-gap semiconductors like GaAs,[1] $GaAs_XP_{1-X}$,[2] InAs,[3] InP,[4] etc., but not yet for indirect gap materials such as Ge, Si and GaP. Even in the direct gap semiconductors it has been necessary, in most cases, to cool the device in order to obtain carrier degeneracy at relizable injection levels.[5] We propose that laser action should be obtainable in many of the indirect gap semiconductors, and improved in the direct gap ones, if it is possible to supply them with a pair of heterojunction injectors. These should consist of heavily doped semiconductor layers with a higher energy gap than the radiating semiconductor and ideally should be of opposite polarity (Fig. 1).

This proposal is based on the assumption that at sufficiently high carrier injection levels laser action could occur, and at higher temperatures than to date, in most semiconductors, including many indirect gap ones. In the latter ones this could take place by spill-over of electrons from their lowest energy valleys into the region of the smallest direct gap. In many semiconductors

* Received October 14, 1963.

[1] R. N. Hall, *et al.*, "Coherent Light Emission from GaAs Junctions," *Phys. Rev. Lett.*, vol. 9, pp. 366–368, Nov., 1962; M. I. Nathan, *et al*, "Emission of Radiation from GaAs pn Junctions," *Appl. Phys. Lett.*, vol. 1, pp. 62–64, Nov., 1962.
[2] N. Holonyak, and S. F. Bevacqua, "Coherent (Visible) Light Emission from $Ga(As_{1-X}P_X)$ Junctions," *Appl. Phys. Lett.*, vol. 1, pp. 82–83, Dec., 1962.
[3] I. Melngailis, "Maser Action in InAs Diodes," *Appl. Phys. Lett.*, vol. 2, pp. 176–178, May, 1963.
[4] K. Weiser and R. S. Levitt, "Stimulated Emission from Indium Phosphide," *Appl. Phys. Lett.*, vol. 2, pp. 178–179, May, 1963.
[5] An example of room temperature operation at very high current density has been given by G. Burns and M. I. Nathan, "Room-Temperature Stimulated Emission," *IBM J. Res. and Dev.*, vol. 7, pp. 72–73, Jan., 1963.

the direct gap is only a little larger than the indirect gap, for example by 0.14 ev in Ge and by 0.35 ev in GaP, not however in Si (by 1.5 ev). Wide-gap injectors should be capable of providing the necessary injection levels to raise the electron quasi Fermi level above the energy at $k=0$, at least for those semiconductors that have an only slightly raised gap, and certainly for the direct gap ones.

The high injection efficiency of individual heterojunctions as wide-gap emitters in transistors was pointed out earlier.[6] In the device proposed here their effectiveness is greatly multiplied by their use in pairs. We consider the example of Fig. 1. An inner semiconductor base with a thermal energy gap ϵ_B and the thickness w is sandwiched between two outer semiconductor injectors with the gaps $\epsilon_I=\epsilon_B+\delta$. As in a transistor, the base width w shall be large compared to the Debye length, but small compared to the diffusion length in the base. The two injectors shall be heavily doped on both sides, and, in our case, to opposite polarities. For simplicity we also assume: a) The heterojunctions are sufficiently gradual, so that the band picture is as shown in Fig. 1, whith no discontinuities of the band edges, b) the density of states for electrons equals that for the holes and the two are the same in both semiconductors, and c) the Fermi level pentrations Δ_I into the bands are the same in both injectors. These simplifying assumptions could easily be removed.

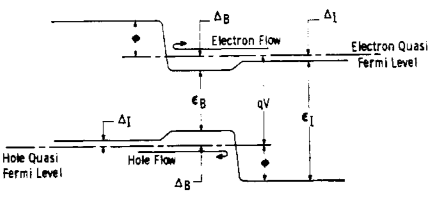

Fig. 1—Heterojunction laser structure with applied bias; $\epsilon_I+\Delta_I>qV>\epsilon_B+2\Delta_I$.

If a forward bias V is applied to such a structure, both holes and electrons will be injected into the base. Because of the existence of the potential barriers at the heterojunctions these carriers cannot readily flow off, so long as $qV<\epsilon_I+\Delta_I$; they must pile up in the base region. As a result the electrons will be very nearly in equilibrium with the n^+ injector and they will be governed by its Fermi level. Similarly the holes will be governed by the p^+ Fermi level. Electroneutrality requires the two injected densities to be equal. Consequently, the separations of the two band edges from their respective Fermi levels must be equal, too.

For $qV>\epsilon_B$ the two Fermi levels penetrate into the allowed bands by the amount

$$\Delta_B = 1/2(qV - \epsilon_B) \qquad (1)$$

and the injected carrier gas becomes degenerate. In the bias range

$$\epsilon_I + \Delta_I > qV > \epsilon_B + 2\Delta_I \qquad (2)$$

the Fermi level penetration in the base region exceeds that in the two injectors. In a homogeneous gap structure the potential barrier opposing the outflow of carriers from the middle region would have vanished at this point. But in the heterojunction structure the barrier still has the height

$$\Phi = \epsilon_I + \Delta_I - qV = \delta + \Delta_I - (qV - \epsilon_B) \qquad (3)$$

from the Fermi level in the base. So long as $\Phi>0$ a degenerately doped injector will be able to maintain the density in the base region against whatever outflow takes place into the opposite injector, which is the reason for the upper voltage limit in (2).

The injected carrier density, then, exceeds the density in the injectors, a situation impossible to achieve with homogeneous-gap junction structures. This is the situation shown in Fig. 1. At the upper end of the voltage range of (2), $\Delta_B=\delta/2$, and this quantity can easily be a sizeable fraction of 1 ev, for example about 0.35 ev for the combination Ge-GaAs. Degenerate spill-over into the Ge central valley would occur already for $\Delta_B\approx 0.14$ ev, which is considerably below $\delta/2$.

Structures with identically doped injector electrodes and an oppositely doped base are also possible and are probably easier to build. In this case the two injectors will have to be at the same potential, forward biased with respect to the base. The heterojunctions will again be efficient injectors of one carrier polarity, preventing the outflow of the neutralizing carriers of opposite polarity. There is no potential barrier for the injected carriers. But their outflow will still be substantially reduced because it would have to take place through the thin base, parallel to the junction. Even for conventional injection lasers the transverse junction dimensions commonly are at least of the order of a fraction of a millimeter. For such or even larger dimensions the resulting concentration gradients would be comparatively shallow, and because of this and because the base is likely to be thin compared to the transverse dimensions the outflow current would be low. Because of inevitable strong surface recombination one could not expect this low outflow if one of the junctions had been replaced by a surface.

The performance of lasers with identically doped injectors would, thus, fall in between that of conventional injection lasers, and that of oppositely doped heterojunction lasers, being much superior to the former but not quite as good as the latter. For such injector materials like ZnSe and ZnTe that appear to be available only in one polarity only the identically doped version is possible.

Because of the wider band gap of the injector the light from a heterojunction laser could be extracted through the injector, transverse to the plane of the junctions. This will not automatically be the case because the base thickness will often be much smaller than the lateral extension of the base and there will therefore be more gain in the parallel escape mode. However, if desired, this difference can obviously be overcome by a suitable device design. If this is done it is advisable to use fairly thin injector layers, in order to limit losses by free-carrier absorption in the injectors. In this way coherence over a much larger area could be obtained than in an ordinary injection laser.

The predicted injection levels will occur only if radiationless recombination processes do not assume catastrophic magnitudes. The two main processes are volume losses via recombination centers in the base region, and recombination at the heterojunctions proper.

We have considered both processes, and have concluded that, in high-quality Ge at least, recombination currents, say, in excess of 1000 A/cm^{-2} could be caused only by the interface dislocations that arise from the lattice mismatch between base and injectors. For the Ge-GaAs system this mismatch is 0.7×10^{-3}. Of the resulting dislocations all those will contribute to the recombination current that fall onto the lower-gap base side of the interface. The experimental values for the recombination efficiency of dislocation in Ge vary over a 1000:1 range.[7,8] If all the interface dislocations are assumed to contribute and if the most pessimistic values for the recombination efficiency[7] are chosen a rough calculation indicates recombination currents of the order 30,000 to 100,000 A/cm^2, which would be sustainable only pulsed and which would very severely limit the practicality of the proposed device.

Possibly the recombination efficiencies are lower than the most pessimistic values, but in any case these considerations teach the importance of a very close lattice fit and of retaining as many interface dislocations as possible on the high-gap injector side, where they would not contribute to the recombination current. The latter objective can be achieved by epitaxially growing the injector onto a pre-existing base at a sufficiently low temperature, the first by a judicious selection of semiconductor materials and by improving the lattice fit by using alloy mixtures. For example, the already small misfit in the Ge-GaAs system can be made to vanish by alloying either the Ge with about 1.8 per cent Si or the GaAs with about 1.0 per cent GaSb or InAs.

We have investigated the majority of the possible combinations containing Ge, Si, III-V compounds and II-VI compounds. There are at least another two pairs with lattice misfits below 10^{-3} (HgSe-ZnTe and InSb-CdTe) and at least an additional 27 pairs with misfits below 10^{-2}, even without alloying. Besides Ge-GaAs the most interesting combination appears to be GaP-AlP, which might provide an indirect-gap visible laser. Perfect lattice fit could be obtained by alloying 4 per cent GaAs to the GaP. However, at present the Ge-GaAs system appears to be the most immediately realizable one.

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[8] A. D. Kurtz, S. A. Kulin, and B. L. Averback, "Effects of Growth Rate on Crystal Perfection and Lifetime in Germanium," *J. Appl. Phys.* vol. 27, pp. 1287–1290, Nov., 1956.