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Optical Mixing of Coherent and Incoherent Light

The development of maser sources of intense monochromatic light has opened a new field of experimentation in optics where nonlinear terms in the optical polarizability of transparent piezoelectric materials make possible the generation of optical harmonics[1,2] and the mixing of light waves having different directions of propagation[3] and frequency.[4] In these previous mixing experiments the intense, relatively coherent outputs of optical masers were used. We report here the mixing of a ruby maser signal with spectral lines of a mercury lamp which are quite broad and relatively weak.

In the present experiment a collimated beam from a mercury lamp is incident on a piezoelectric crystal. The direction of this beam is collinear with the unfocused maser beam. The sum frequency signal leaving the crystal is passed through a monochromator and detected photoelectrically. The output at the sum frequency is maximized by satisfying the condition for momentum balance in the piezoelectric crystal: $\mathbf{k}_b = \mathbf{k}_r + \mathbf{k}_g$, where the subscripts b, r and g refer to the sum, the optical maser and the spectral line frequencies, respectively. As already pointed out in the case of harmonic generation,[2,3] this can be done in uniaxial crystals for which the birefringence is greater than the dispersion. In the case of a negative uniaxial crystal such as potassium dihydrogen phosphate (KDP), the input beams are polarized as O-rays, and are passed through the crystal at a certain angle θ_0 to the optic or z-axis, with the projection on the x-y plane at 45° to the x-axis. The output is then an E-ray which must have an index n_b given by the momentum condition for parallel beams, $n_b/\lambda_b = n_r^O/\lambda_r + n_g^O/\lambda_g$; the angle θ_0 is given by $\sin^2\theta_0 = [(1/n_b)^2 - (1/n_b^O)^2]/[(1/n_b^E)^2 - (1/n_b^O)^2]$, where the superscripts O and E denote ordinary and extraordinary indices, respectively. Using Giordmaine's[3] index of refraction data for KDP, θ_0 for mixing of the mercury green (5461 A) and yellow (5770, 5790 A) lines with the ruby maser (6943 A) is 56.9° and 55.0°, respectively. The same data give $\theta_0 = 50°$ for harmonic generation with the ruby maser. The KDP crystal used in the present work was cut perpendicular to this latter direction and rotated to attain other values of θ_0.

The experiments were carried out with a pulsed ruby maser having a beam width of about one-half degree, and a PEK 109 high-pressure mercury arc lamp operated continuously at 100 w. This lamp has an arc diameter of 0.012 in., and light from it was collimated into a beam having a width of one-half degree. The beams were superposed with the aid of a 45° dichroic mirror which transmitted the maser signal and reflected the mercury green and yellow lines. The combined beams passed through a KDP crystal which was 0.6 cm thick and cut as previously described. The crystal was mounted on a horizontal rotating table, with the optic axis parallel to the table. The output of the maser was polarized vertically, making the light an O-ray in the crystal. Light emerging from the crystal at the sum frequency was focused by a quartz lens onto the slit of a double-prism monochromator and detected with a photomultiplier at the exit slit. The output of the photomultiplier was displayed on an oscilloscope whose sweep was triggered by the maser trigger pulse. Suitable filters were placed in front of the maser, the mercury lamp and the monochromator to attenuate unwanted radiation.

The average power in the maser pulse at the crystal was about 1000 w, while the power in the mercury green line was about 0.02 w. The spectral width of the mercury lines was about 25 A because of pressure broadening. The yellow lines at 5770 A and 5790 A were assumed to be a single line at 5780 A for purposes of calculation.

The mercury green and yellow lines were each mixed with the ruby maser. With the crystal oriented for maximum output, i.e., at θ_0, the sum frequency signals were of the order of 10^{-9} w, which was well above the background due to stray light and photomultiplier dark current. The wavelengths of the signals were not accurately measured but fell at the calculated values of 3056 A and 3155 A for the green and yellow lines, respectively, within the 70 A pass band of the monochromator.

The difference between the value of θ_0 for harmonic generation and mixing of the mercury green and yellow lines was $8.0° \pm 0.3°$ and $5.7° \pm 0.4°$, respectively. These are in reasonable agreement with the calculated values of $7° \pm 1°$ and $5° \pm 1°$, respectively, using indices of refraction mentioned above, and using the Cauchy equation with a term in $1/\lambda^2$ only.

By inserting suitable polarizers in the optical system it was found that (1) mixing occurred only when the output of the mercury lamp was polarized as an O-ray and (2) the sum frequency output was an E-ray. Both results are consistent with the nonlinear theory for KDP.

In a mixing process where one signal is much weaker than the other and where the nonlinearity is not saturated by the larger signal, the output should be proportional to the product of the two input powers. This was confirmed by an experiment in which the power in the mercury green line was varied with calibrated attenuators. The output power at the sum frequency was found to be directly proportional to the input power, as expected.

In mixing experiments of this type, the optical maser signal may be regarded as a pump,[5] in analogy with a microwave variable reactance frequency converter. The pump causes a change in the dielectric constant which travels through the medium with the phase velocity of the maser signal. Another coherent signal collinear with the pump can mix with it to produce a sum signal, whose amplitude will build up through the crystal if the condition for momentum balance is satisfied. In a crystal of thickness d, the sum frequency output will be zero when the momentum mismatch $\Delta \mathbf{k} = |\mathbf{k}_r + \mathbf{k}_g - \mathbf{k}_b| = \pi/d$ (Ref. 6). Thus, mixing will occur over a spectral bandwidth determined by the dispersion and over an angular bandwidth determined by the birefringence. The mixing of the maser signal with a spectral line can be understood by regarding the line as a Fourier sum of plane monochromatic components with random phases. Each component falling within the spectral and angular bandwidths of the crystal will contribute a sum frequency component. A detectable output at the sum frequency, therefore, can be expected when coherent and incoherent signals are mixed.

The role of the bandwidths in the experiments described here will be discussed briefly. For the present crystal, the spectral bandwidth (separation of the input wavelengths giving zero output) is estimated to be about 8 A. As the mercury lines have a width of about 25 A, a detailed examination of the spectral shape of the sum frequency signal would be of interest. The angular bandwidth for the present crystal with a strictly plane wave pump is about 0.07°. The maser output actually had a spread of about one-half degree and the detection system had an acceptance angle of one degree. Under these conditions, there will be an appreciable contribution from the mixing of nonparallel beams over most of the half-degree spread of the green and yellow beams.

Because of the traveling wave nature of the process, where the sum signal energy stays with a given pump cycle, a spectral emission line would satisfy the pumping frequency requirement but, since the nonlinearity of the dielectric is rather small, the mixed signal of two spectral lines would be very small. A maser light beam is required to give a sufficiently large change in dielectric constant to yield a detectable signal.

References

1. P. A. Franken, A. E. Hill, C. W. Peters and G. Weinreich, *Phys. Rev. Letters* **7**, 118 (1961).
2. M. Bass, P. A. Franken, A. E. Hill, C. W. Peters and G. Weinreich, *Phys. Rev. Letters* **8**, 18 (1962).
3. J. A. Giordmaine, *Phys. Rev. Letters* **8**, 19 (1962).
4. P. D. Maker, R. W. Terhune, M. Nisenoff and C. M. Savage, *Phys. Rev. Letters* **8**, 21 (1962).
5. R. W. Landauer, IBM Research Note NC-16, Sept. 25, 1961.
6. J. A. Armstrong, N. Bloembergen, J. Ducuing and P. S. Pershaw, Technical Report 358, Cruft Laboratory, Harvard University, Cambridge, Mass., March 20, 1962.

Received May 25, 1962