Figure 2 is an ultrasonic hologram of the threaded end of a 1/2 in. diameter bolt possessing thirteen threads per inch. Figure 3 shows the image formed by this hologram. Figure 4 is a conventional photograph of the bolt. The speckled nature of the image formed by the ultrasonic hologram is typical of images formed with coherent radiation.[2,3]

The three-dimensional quality of the images is readily observed by continuously scanning the magnifying lens to focus at different image planes. Various other objects have been imaged by ultrasonic holographic techniques, including a small hole inside an aluminum block. Objects have been imaged at various angles to the hologram plane.

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OPTICAL HETERODYNE MEASUREMENT OF NEON LASER'S MILLIMETER WAVE DIFFERENCE FREQUENCY*

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We report detection and measurement of the millimeter wave difference frequency between two near laser lines at 1.152 μ. The two spectral transitions, separated by 2.26 Å, oscillate in pure neon in a single laser device, producing about 150 μW total power in several longitudinal modes. The many resulting 51.3-kmc beat frequencies have been studied by optical heterodyne techniques. A type of diode has been found which has enough microwave sensitivity *and* enough optical sensitivity to combine the optical detector and the microwave heterodyne functions in a single element. The preliminary value for the difference in frequency between the $2S_2 \rightarrow 2P_4$ and $2S_4 \rightarrow 2P_7$ transitions in neon at 150 mtorr is (51,360 ± 150) Mc. This value is not in agreement with the value calculated from Vol. I of Sitterly's *Atomic Energy Levels* (ref. 12).

We report here the first direct measurement of the millimeter wave (51.3 Gc) difference frequency between two transitions simultaneously oscillating near 1.15 μ in a pure neon gas laser. The potential use of radio-frequency techniques to obtain extremely high effective resolution for the study of a variety of atomic physics spectroscopic problems has been apparent since the early days of the gas laser.[1] Indeed, the first measurements of the spectral width of gas laser sources, made by Javan, Bennett and Herriot[2] in 1961, utilized the difference frequencies between several oscillations at the cavity longitudinal resonance frequencies in their helium-neon laser. Patel and Sharpless[3] in 1964 detected beat frequencies as high as 17.7 Gc using special electrochemically etched germanium point-contact photodiodes. The bromine-argon laser[4] source used in their experiments emitted four lines near 8446 Å with difference frequencies from 3.9 to 21 Gc. In addition, several workers have used high-power pulsed laser sources to generate and study microwave difference frequencies with traveling-wave phototubes,[5] parametric difference frequency generation[6] and various high-speed photodevices.[7]

The laser used in the present study is based on the work by W. R. Bennett, Jr. and J. W. Knutson, Jr.,[8] in which they obtained simultaneous oscillation on the neon doublet at 1.1523 Å in a pure neon discharge at low pressures. These workers obtained about 1.5 mW, multimode, from their 3-m confocal device, with a 3 or 4 to 1 power ratio between the pair of lines. They called attention to the deleterious effect of relatively small amounts of helium in reducing the gain of the weaker transition of the pair ($2S_4 \rightarrow 2P_7$ at 1.15282) and suggested electron impact pumping in pure low-pres-

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sure neon. The other line of this beat note pair is the strong 1.15259-μ line ($2S_2 \rightarrow 2P_4$) initially studied in the He-Ne laser.[2] On the basis of Bennett's gain data (~1%/m) a 30-cm laser was constructed. This device did in fact oscillate simultaneously single mode in the two lines, but the output power of a few microwatts proved inadequate for the first search.

The present observations were made with a 138-cm pyrex discharge tube, ID of 3.9 mm, operated at about 150 mtorr in pure neon. A large aluminum cold cathode (50 mm ID by 30 cm long) was employed to minimize sputtering and consequent gas cleanup. With a 500-cc reservoir, the tube can be operated at 40 mA for about 20 hr before the gas pressure has decreased excessively—say 10%. The discharge tube is mounted in a 3″ OD by 5/16″ wall quartz tube which has lightweight adjustable electrostrictively-driven mirror mounts attached to its ends with epoxy. Longitudinal mode spacing is 109 Mc. One mirror is of 3-m radius, coated to 99.9% reflectivity. The output mirror is of 2.15-m radius, specially coated to provide 99.5% reflectivity at 1.152 μ and only 60% reflectivity at 1.115 μ, the wavelength of the $2S_4 \rightarrow 2P_8$ transition which otherwise dominates the desired $2S_4 \rightarrow 2P_7$ transition at 1.15282 μ. With this special mirror, the outputs of the two desired transitions can be made essentially equal by appropriate choice of pressure and current. Under the same conditions, but with broad-band mirrors, the $2S_4 \rightarrow 2P_7$ output is a factor of 10 weaker due to the competition for excited atoms in the $2S_4$ level by the higher gain $2S_4 \rightarrow 2P_8$ oscillation.[9]

The laser is supported by foam plastic on a massive cast-iron surface table, as is the scanning Fabry-Perot interferometer used for analyzing the mode structure of the laser. We observe oscillation in some 10 to 15 longitudinal cavity resonances in each transition. With no further precautions, the frequency jitter appears to be less than 10 Mc and mainly periodic at 30 cps, measured in the daytime with vacuum pumps running in adjacent labs. For such suitably small shifts, the fact that the laser cavity Q is high compared with that of the Doppler-broadened atomic transition results in simultaneous and essentially equal frequency shifts of all the oscillations together. Actually, for the general tuning case—cavity modes not centered in the Doppler gain curve—the several longitudinal modes are statically shifted slightly from the $c/2L$ positions by mode-pulling phenomena.[10] Thus, each 51-kmc beat note appears (under low resolution) to be about a megacycle wide. However, the higher resolution provided by a communications receiver shows the apparent width to be composed of a number of sharp components, the <5 kc spectral width of which appears to be due primarily to klystron power supply ripple.

Thus the spurious mechanically induced line width of the beat note—less than 5 kc—is much smaller than the ~10 Mc excursions of the optical frequencies themselves. This correlation of the two optical frequencies giving rise to a narrow beat note spectrum provides strong motivation for the use of simultaneous oscillations within one laser cavity, rather than separate laser devices, at least if simplicity or resolution are important considerations. Since even different spectral transitions have their (small) changes in frequency correlated by oscillation in the same laser cavity, one could, if forced, consider the use of two separate gas discharge cells in series to optimize the inversion parameters separately for the two lines of interest.

Although separation of the optical detection and microwave heterodyne conversion processes can probably best be made to approach the optimum sensitivity limit (by the use of separate devices optimized for each function), we have chosen to combine these two functions in a single, suitable diode. This approach was essentially dictated by the necessity to search with high sensitivity the 600-Mc interval at 51 Gc covered by the beat frequency as calculated from different sets of spectroscopic term values.

We have tried several commercial junction photodiodes as well as an adjustable point-contact silicon device fabricated in the style of millimeter wave frequency multipliers. However, none appear to be as reliable and effective as a "hot carrier diode"[11] designed to be used as superheterodyne mixer in the range up to a few gigacycles. The most significant property operationally of this type of diode is that it does have both enough optical sensitivity (quantum efficiency about 10^{-5} at 1.15 μ) and enough microwave sensitivity (about 0.3 μ A/mW at 50 Gc) to allow separation of the "tune-up" and "frequency search" operations. The beat note was first detected by chopping and narrowbanding, using the diode under zero-bias conditions. The 51-Gc local oscillator applied to the resistance of the diode heterodyned the 51-Gc component of photocurrent down to the 60 mc amplified by our IF amplifier. This operation as a photomodulated microwave resistor was marginally successful, as predicted from knowledge of the laser power, measurements of the diode's quantum efficiency and data on its microwave equivalent circuit parameters. However, it was very quickly discovered that a reverse bias increased the detection sensitivity dramatically—100 to 10,000 times—even though the diode is reversed biased during the *entire* microwave cycle. Apart from the obvious remarks that the capacitive component of microwave crystal current is involved and is somehow modulated by the beat component of the photocurrent, we shall resist the temptation to speculate on the physics of the detection process. Operationally, the conversion gain appears to increase dramatically for only a few volts reverse bias, then increase slowly, and then increase again sharply as the avalanche condition is approached at about 30 V. In this latter region the noise also increases rapidly, more so at 30-Mc IF center frequency than at 60 Mc as might be expected if a $1/f$ noise spectrum predominates.

With a laser output power of about 180 μW distributed among about 15 oscillations in the two optical transitions, we observe about 2×10^{-14} W of 30-Mc power available from the diode in the strongest 51-kmc beat note. This power corresponds to a signal-to-noise ratio of about 30 to 1 with a 1-Mc IF passband followed by a post-detection bandwidth of 1 kc. A "spectrum analyzer" presentation of the filtered output of the 30-Mc IF amplifier is shown in Fig. 1 as the vertical deflection of the lower trace. The horizontal deflection is provided by the klystron's repeller sweep voltage and hence corresponds to a (nonlinear) frequency axis. The upper and lower sidebands with respect to the klystron local oscillator are denoted by U and L. The subscripts refer to the number of $c/2L$ intervals away from line center. The apparent strength of the several lines is heavily distorted by the frequency dependence of the microwave adjustments. In addition, about five additional pairs of lines are easily detected above and below the limits of frequency sweep available in Fig. 1. By virtue of the heterodyne operation, the klystron frequency matches the beat frequency in the center of the wider frequency interval, such as indicated by the frequency marker pip just visible on the upper trace.

With the measured optical quantum efficiency η of about 10^{-5}, the "transfer impedance" of the diode, R_{eq} defined by $P_{30\text{Mc}} = R_{\text{eq}} i^2 = R_{\text{eq}} (\eta P_{\text{laser}})^2$, turns out to be about 10^5 Ω. This value appears to be limited very seriously in the present case by our inability to perfectly match the diode to our klystron of nominally 100-mW output. Tuning of the diode is accomplished by repositioning the diode within its impedance-transforming short section of coax line and by sliding this coax line with respect to a commercially tuned waveguide to coax transformer (diode mount). A small hole in the side of the coax allows the two laser frequencies to be focused on or near the active junction through the diode's glass encapsulation. The necessary angular collimation of the two lasers is automatically provided by oscillation in the same laser device.

The 51.3-Gc frequency is measured by heterodyne against the sixth harmonic of a X-band stable source. The necessary few milliwatts at 8560 Mc is provided by TWT amplification of the output of a varactor driven at 130 Mc by a stable oscillator, the frequency of which is counted by a digital frequency meter.

The preliminary value thus determined for the frequency difference between the centers of the $2S_2 \rightarrow 2P_4$ and $2S_4 \rightarrow 2P_7$ transitions in pure neon[20] at 150 mtorr is (51,360 ± 150) Mc. The assigned uncertainty is due almost entirely to the uncertainty in setting the laser simultaneously to the centers of the two transitions. It is interesting to compare our result with published spectroscopic values. Mrs. C. M. Sitterly's tables[12] give the value 50,930 Mc for the difference frequency, a result which is outside the known errors in the present experiment. However, the recent very precise results of Minnhagen[13] for the $2S$ levels taken to-

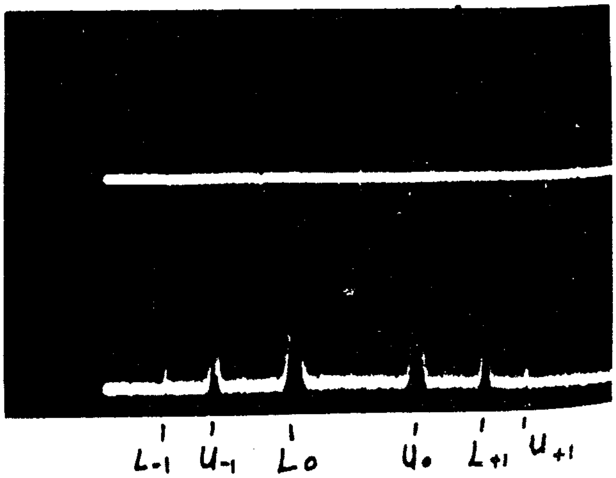

Fig. 1. Frequency-swept display of IF amplifier output (lower trace). Upper trace shows heterodyne frequency marker at 51,360 Mc. Horizontal scan, provided by klystron repeller voltage, is (nonlinear) frequency scan. U and L denote upper and lower sideband, respectively, with respect to klystron frequency. Subscripts denote number of $c/2L$ intervals away from line center. $U_0 - L_0$ is 2 times the 30-Mc IF frequency. $L_0 - U_{-1}$ is 49 Mc, as is $L_{+1} - U_0$.

gether with the $2P$ levels from ref. 12 give the value 51,267 Mc, which is within our present experimental uncertainty. Since in ref. 12 the $2S_2$ level is given only to 10 milliwave numbers, it is naturally suspect, but comparison with Minnhagen's results reveals only a 0.4 milliwave-number discrepancy. However, the $2S_4$ level does appear to be in error, being given as 11.5 milliwave numbers too high by comparison with Minnhagen.

The uses of this microwave optical heterodyne technique seem to include the following:

1) Precision optical heterodyne spectroscopic measurement of the optical term differences of the relevant atomic levels.[14]

2) Study of the pressure- and current-dependent shifts of two similar spectral transitions. Since the method is sensitive only to the difference in shifts, it might be hoped to measure another useful combination of parameters appearing in pressure-shift theory.

3) Measurement of the difference in frequency between two laser lines with difference in wavelength simultaneously measured by long-path interferometric techniques to provide a precision velocity of light measurement. A 30-m evacuated Fabry-Perot interferometer, which has been constructed in an unused mine near Boulder, may be suitable for this purpose.[15]

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PHOTOCONDUCTIVITY IN *p*-TYPE SINGLE-CRYSTAL PbS FILMS

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Photoconductivity has been observed in *p*-type single-crystal films of PbS. The results suggest that the photoconductive mechanism in these films is the same as that in the highly sensitive *p*-type polycrystalline PbS detectors.

Polycrystalline lead sulfide films have been in use for many years as photoconductive detectors in the near infrared. It has been generally concluded that the sensitivity of these films is related to their highly polycrystalline structure. However, there has been considerable disagreement over the details of the photoconductive processes involved.

Electrical properties of single-crystal films of PbS have been investigated by Berlaga, Vinokurov, and Konorov[1] and by Zemel, Jensen, and Schoolar.[2] Soule and Cashman[3] have observed a concentration inhomogeneity-related photoresponse in bulk crystals of *p*-type lead sulfide. In addition, Bykova[4] has detected photoconductivity in *n*-type single-crystal films.

This Letter reports the first observation of photo-