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R-5—Enhancement of Optical Receiver Sensitivities by Amplification of the Carrier

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Abstract—The amplification before detection of the carrier of a modulated optical signal by a narrow-band quantum amplifier enhances the signal-to-noise ratio, particularly when the signal wavefront is distorted. A further improvement is obtained by using a combination of wide-band and narrow-band quantum amplifiers. The practical application of these schemes requires a degenerate regenerative ring-type amplifier capable of amplifying arbitrary transverse field configurations. Experiments show that such an amplifier with a gain of 24 dB and a bandwidth of 1 MHz is feasible. The incident beam axis can be displaced by as much as ten times the beam-waist radius without losing more than 4 dB in gain. Frequency modulation may be converted into amplitude modulation by the phase shift introduced in the carrier.

I. Introduction

A FEW lasers are presently available that exhibit a relatively large gain and could be used before detection to enhance optical receiver sensitivities [1]. However, because of its spontaneous emission, a quantum amplifier introduces an optical noise power proportional to the optical bandwidth and to the number of transverse modes to be amplified [2]. When the signal wavefront is distorted because of multimode operation of the source, propagation through a turbulent atmosphere or imperfections of the optical components, the number of transverse modes may be quite large. A quantum amplifier designed to amplify such a distorted signal may not improve the signal-to-noise ratio. Furthermore, the information bandwidth is restricted to the optical linewidth, which is as small as 50 MHz in the case of CO_2 lasers. These two difficulties are overcome if we amplify only the carrier of a modulated signal, the sidebands being simply transmitted [3]. In that case, the bandwidth of amplification can be made very narrow and the information bandwidth is essentially limited by the detector capability. Ideally, an infinitely narrow-band quantum amplifier would not introduce any optical noise. It will be shown that the SNR may approach the SNR of a homodyne receiver for a single transverse mode signal.

By using both wide-band and narrow-band quantum amplifiers, it is possible, in principle, to approach half the maximum attainable SNR for any signal power, any value of the detector quantum efficiency and any degree of signal distortion.

These conclusions assume that the carrier and the sidebands experience exactly the same phase-front distortions in spite of their difference in frequency. It has been shown for random distortions, that this assumption is valid at optical wavelengths [4].

The practical application of the scheme depends on the feasibility of ring-type degenerate regenerative amplifiers. A regenerative amplifier is known to provide high gains and small bandwidths [5]. However, it is usually designed for single transverse mode operation. To amplify arbitrary transverse field configurations the cavity must be degenerate. Linear degenerate cavities were proposed by Pole [6] and Hardy [7]. Other simple configurations, including ring-type cavities were discussed by the author [8]. Ring-type configurations with one semitransparent mirror to couple the carrier in and out are particularly suitable for this application because the sidebands are directly reflected to the detector. In addition, no power is reflected back to the source. This feature improves the stability when a number of regenerative amplifiers are used in cascade.

Experimental results obtained with regenerative amplifiers using the large-gain low-noise transition in HeXe at $\lambda = 3.508\ \mu$ are discussed here.

II. Discussion of the Sensitivity of the Proposed Receiver

In this section we calculate the improvement in SNR ratio, which may be expected from the proposed receiving scheme under idealized conditions.

A. Description of the Transmitter

The transmitter is supposed to deliver a linearly polarized optical signal modulated sinusoidally in field at a frequency F with a modulation index of 100 percent. This transmitter is shown in Fig. 1(a). If we call P_s the peak power, the instantaneous power is

$$P(t) = \frac{P_s}{4}(1 + \cos 2\pi F t)^2. \tag{1}$$

According to (1), the power in the carrier is $P_s/4$ and the power in each of the two sidebands is $P_s/16$. The losses and depolarization effects in the transmitting medium are neglected. The signal power at the input of the receiver is supposed to be arbitrarily distributed among the n lowest order transverse Hermite–Gauss modes.

B. Description of the Receiver

As shown in Fig. 1(b), the proposed receiver is composed of the three following components:

1) a wide-band quantum amplifier of gain G and bandwidth $2B$ amplifying both the carrier and the sidebands,

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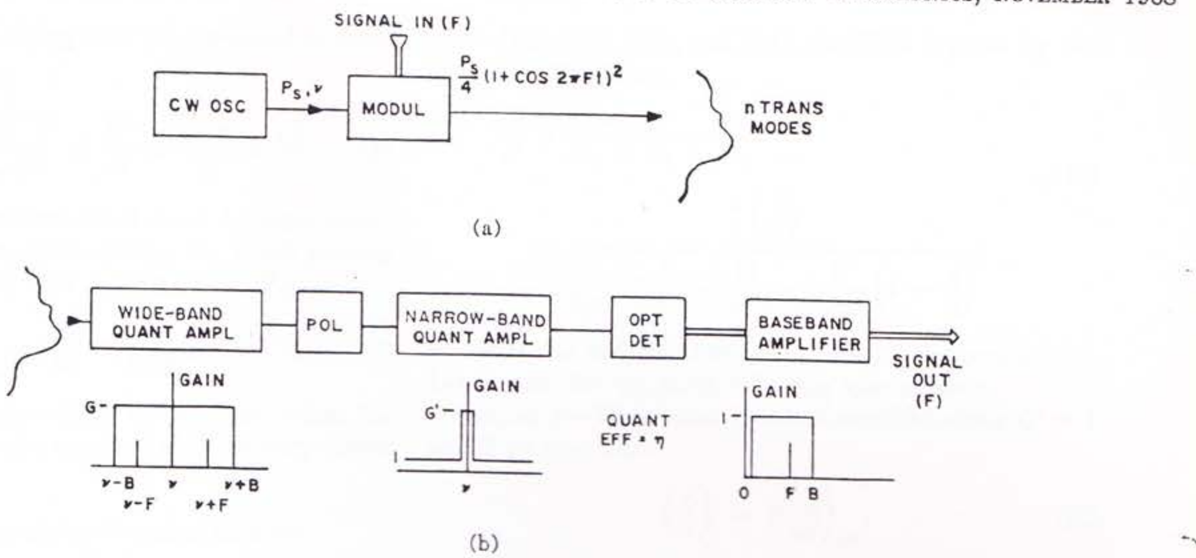

Fig. 1. Block diagram of the proposed receiving scheme. (a) Transmitter modulated sinusoidally in field. (b) Receiver incorporating a wide-band and a narrow-band quantum amplifier.

followed by a perfect polarizer. The fraction of the optical noise power generated by spontaneous emission which reaches the detector is given by [2]

$$P \equiv nP_0 = nh\nu 2B(G-1) \tag{2}$$

where $h\nu$ is the photon energy and $2B$ the optical linewidth. It is assumed that the low level of the transition is depopulated. P_0 is the noise power per mode and n is the number of transverse modes to be amplified, assuming that the other modes are filtered out [2].

2) a narrow-band quantum amplifier with a gain G' at the carrier frequency and unity elsewhere. Because of its narrow bandwidth the optical noise power that it generates is neglected.

3) a square law optical detector of uniform quantum efficiency η, unlimited area, and unity current gain. This detector is followed by a baseband amplifier with a gain taken, for simplicity, as unity for frequencies going from nearly zero to B, and as zero outside this band. The total gain of the two quantum amplifiers is supposed to be large enough to make the detector and baseband amplifier noise negligible. This last assumption will be reconsidered at the end of this section.

Let us recall the basic properties of spatial square-law detectors. At a given point of its surface the detector generates a current density proportional to the instantaneous optical power density in a given polarization state. The proportionality constant is $\eta e/h\nu$, where e is the electron charge. The total current $I(t)$ is the integral over the detector plane of the current density. There is, in addition, a shot noise

$$N_1(t) = 2eI(t)B. \tag{3}$$

When two CW optical signals of powers P_1 and P_2, with the same transverse field configurations and the same polarizations are incident on the detector, the total optical power varies sinusoidally versus time at a frequency equal to the difference of frequency between the two signals. The resulting low-frequency power at the output of the detector is

$$S = 2\left(\frac{\eta e}{h\nu}\right)^2 P_1 P_2. \tag{4}$$

If, instead, we have 1) a CW optical signal of power P_1 at a frequency ν, arbitrarily distributed between the n lowest transverse modes and 2) an optical noise with a power *per mode* P_0 and a spectrum limited to the interval $\nu - B$ to $\nu + B$, the low-frequency beat power is

$$N_2 = 2\left(\frac{\eta e}{h\nu}\right)^2 P_1 P_0. \tag{5}$$

Note that only one noise mode contributes to that part of the detector noise. There is, in addition, the noise resulting from the optical noise itself (noise–noise beat)

$$N_3 = \frac{3}{4} n \left(\frac{\eta e}{h\nu}\right)^2 P_0^2. \tag{6}$$

This result can be derived from the statistics of the optical noise field, taken as Gaussian for each mode. A factor $\frac{3}{4}$ is introduced in (6) because part of the total LF noise power falls above the baseband.

C. Ideal Receiver

For later comparison, let us calculate the expression of the maximum attainable SNR. It is obtained when the signal is applied to a noiseless detector of unity quantum efficiency. In order to restore the linearity the detector is followed by a "square rooter" with an output $i = \sqrt{I}$, where I is the detected current [1]. The LF signal power at the output of the detector is, from (1),

$$S_0 = \overline{(i - \bar{i})^2} = \frac{1}{2}\frac{e}{h\nu}\frac{P_s}{4} \tag{7}$$

where the upper bar indicates a time average.

The shot noise power falling into the baseband is, from (3),

$$N_0 = \overline{\delta i^2} = \overline{\left(\frac{\delta I}{2\sqrt{I}}\right)^2} = \frac{\overline{\delta I^2}}{4I} = \frac{2eIB}{4I} = \frac{eB}{2} \tag{8}$$

where δi, δI are small increments of i and I, respectively.

The optimum SNR is consequently, for a 100 percent modulated optical signal with a peak power P_s

$$\left(\frac{S}{N}\right)_{opt} \equiv \frac{S_0}{N_0} = \frac{P_s}{4h\nu B}. \tag{9}$$

This SNR could be approached in practice (when the detector noise is taken into account) only for very strong signals.

D. Signal-to-Noise Ratio of the Proposed Receiver

We will assume that the beat between the two sidebands is negligible in comparison with the beat between the amplified carrier and the two sidebands. Accordingly, the detection is linear. Refering to Fig. 1(b) we see that the carrier power at the detector is $GG'P_s/4$ and the power in each sideband is $GP_s/16$. Replacing P_1 and P_2 by these two values in (4) and multiplying by 4 to take into account the contribution (in phase) of the two sidebands, we get a signal power

$$S = \frac{G^2G'}{8}\left(\frac{\eta e}{h\nu}\right)^2 P_s^2. \tag{10}$$

Since we are interested only in high-sensitivity receivers we will assume that the signal power P_s is much smaller than the equivalent input noise of the wide-band quantum amplifier

$$P_s \ll nh\nu 2B. \tag{11}$$

For later convenience we put $D = P_s/3nh\nu 2B \ll 1$. A detailed analysis shows that, provided that one of the two following conditions are satisfied, $G \gg 1/\eta$ *or* $G'/G \gg 1/D$, only three noise terms are of importance.

1) The shot noise associated with the amplified carrier, given by (3) with

$$I = \frac{\eta e}{h\nu} GG' \frac{P_s}{4}$$

$$N_1 = 2e\frac{\eta e}{h\nu} GG' \frac{P_s}{4} B. \tag{12}$$

2) The beat between the amplified carrier and the optical noise generated by the wide-band amplifier. This term is given by (5) with $P_1 = GG'P_s/4$ and $P_0 = h\nu 2B(G-1)$

$$N_2 = 2\left(\frac{\eta e}{h\nu}\right)^2 GG' \frac{P_s}{4} h\nu 2B(G-1). \tag{13}$$

3) The noise–noise beat power given by (6)

$$N_3 = \frac{3}{4} n \left(\frac{\eta e}{h\nu}\right)^2 (h\nu 2B)^2 (G-1)^2. \tag{14}$$

From (10), (12), (13), and (14), the SNR is given by the following expression:

$$\frac{S}{N} = \frac{S}{N_1 + N_2 + N_3} = \frac{\frac{1}{2}\left(\frac{S}{N}\right)_{opt}}{\frac{1}{2\eta G} + \left(1 - \frac{1}{G}\right) + \frac{1}{2DG'}\left(1 - \frac{1}{G}\right)^2}, \tag{15}$$

where D was defined above and $(S/N)_{opt}$ is given by (9). Let us consider the three following special cases.

Receiver 1—Wide-band quantum amplifier alone: $G' = 1$ and $G \gg 1/\eta$. Then

$$\left(\frac{S}{N}\right)_1 = D\left(\frac{S}{N}\right)_{opt}. \tag{16}$$

With respect to $(S/N)_{opt}$, there is a degradation expressed by the factor $D \ll 1$. The proposed receiving scheme is aimed at avoiding this degradation.

Receiver 2—Narrow-band quantum amplifier alone: $G = 1$, $G' \gg 1/D$. Then

$$\left(\frac{S}{N}\right)_2 = \eta\left(\frac{S}{N}\right)_{opt}. \tag{17}$$

This $(S/N)_2$ is the same as for a homodyne receiver (using a local oscillator) when the signal is in a fundamental mode; it is by far larger when the signal phase front is distorted. Clearly, it is also superior to the wide-band amplifier $(S/N)_1$ for small signals ($D < \eta$), particularly if the number of transverse modes n is large.

Receiver 3—Combined scheme: $G \gg 1/\eta$ *and* $G' \gg 1/D$. Then

$$\left(\frac{S}{N}\right)_3 = \frac{1}{2}\left(\frac{S}{N}\right)_{opt}. \tag{18}$$

In principle, half the maximum attainable SNR is obtained in this case for any input signal, any detector quantum efficiency and any degree of signal distortion.

The gains and powers required from the quantum amplifiers depend on the amount of detector noise that the total noise power $N_1 + N_2 + N_3$ must overcome. If we consider only the thermal noise of the detector load R, and take R as equal to $(C2\pi B)^{-1}$ where C is the detector capacitance, the square of the thermal noise current is

$$N_T = 8\pi KTCB^2. \tag{19}$$

Let us take the following numerical values: $\lambda = 3.5\ \mu$; $T = 290°\text{K}$; $C = 7$ pF; $\eta = 0.2$; $n = 2000$[1]; $B = 100$ MHz; $P_s = 10^{-9}$ watt. From these values, we get $D = 0.015$ and $(S/N)_{opt} = 16.5$ dB. Note that the SNR without any quantum amplifier would be as low as -52 dB.

By comparing N_1, N_2, and N_3 to N_T we determine the gain and saturation powers required from the quantum

[1] If an immersed highly corrected objective is used to focus the signal on the detector, this corresponds to a detector area: $2000 \times \lambda^2 = 0.024\ \text{mm}^2$.

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TABLE I

		Receiver 1 (Wide Band)	Receiver 2 (Narrow Band)	Receiver 3 (Combined)
Wide-Band Amplifier (200 MHz)	Gain	25 dB	0	23 dB
	Power	7.6 μW	0	4.5 μW
Narrow-Band Amplifier (<2.2 MHz)	Gain	0	62 dB	20 dB
	Power	0	384 μW	5 μW
SNR		−2 dB	9.5 dB	12 dB

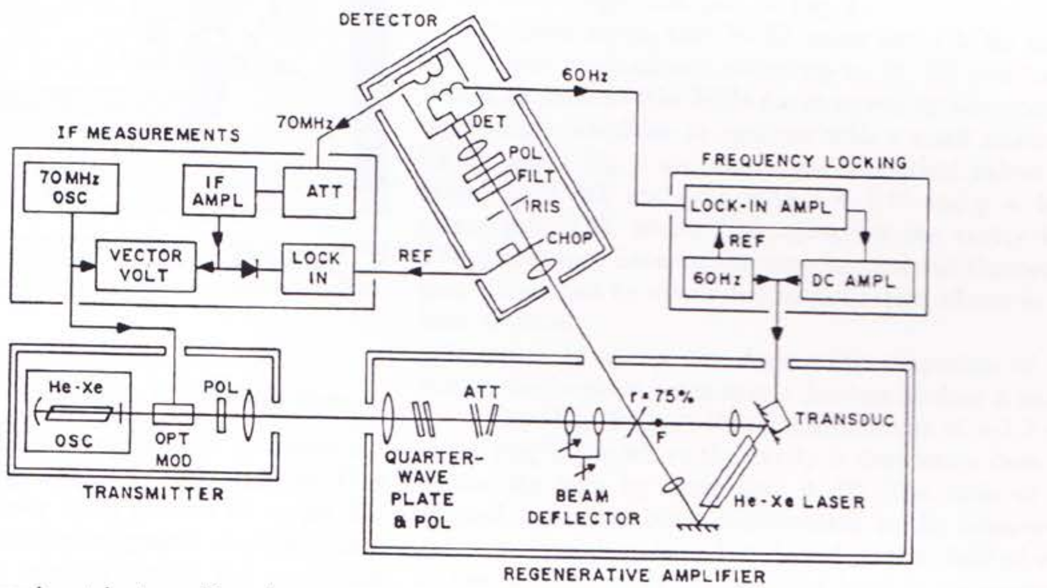

Fig. 2. Experimental setup with a ring-type regenerative amplifier. The detected IF voltage is compared to the modulating voltage with a vector voltmeter. A frequency locking loop keeps the regenerative amplifier close to the transmitter carrier frequency.

amplifiers for Receivers 1, 2, and 3. They are given in Table I, together with the achievable SNR/s.

This table shows that the combined scheme requires less gain and power than Receiver 2 and gives a slightly better SNR. Considering the various sources of noise that were overlooked, the powers actually required may be one or two orders of magnitude higher than shown in Table I.

III. Noise of a Ring-Type Regenerative Amplifier

The optical noise generated by a standing-wave regenerative amplifier was derived by Gordon [10]. Similar results are given here for a ring-type regenerative amplifier. Single-mode linear operation is considered. Let g and r be respectively the single-pass power gain and the input–output mirror power reflectivity. The power gain of the regenerative amplifier is

$$G(\varphi) = \frac{(\sqrt{g} - \sqrt{r})^2 + 4\sqrt{rg}\sin^2(\varphi/2)}{(1 - \sqrt{rg})^2 + 4\sqrt{rg}\sin^2(\varphi/2)} \qquad (20)$$

where φ is the round-trip phase shift, which is essentially equal to kL, where k is the propagation constant and L the round-trip path length. Notice that when $g = 1$, $G(\varphi) = 1$, the output field being merely phase-shifted. $G(\varphi)$ becomes infinite, for $\varphi = 0$, when g approaches r^{-1}. From (20), the 3-dB-bandwidth ΔF is, for $rg \simeq 1$,

$$\Delta F = \frac{c}{2\pi L}\Delta\varphi \sim \frac{c}{\pi L}(1 - \sqrt{rg}). \qquad (21)$$

When rg approaches unity, the product $G(0)\Delta F$, and consequently the noise power, tends to infinity.

Since we are interested only in the noise power fed into the detector, we have only to consider the noise power originating from one end of the laser tube. The integrated noise power is calculated by assuming that the noise spectral density is uniform within the frequency band where $G(\varphi)$ is significant. Then, the noise power turns out to be exactly the same as if we had a straight amplifier with the same gain followed by a passive cavity with the same bandwidth. In contrast, the noise power from one end of a symmetrical standing-wave regenerative amplifier is twice as large.

IV. Experimental Results

Experiments were made to check the feasibility of degenerate regenerative amplifiers and the proposed detection scheme at a wavelength of 3.5 μ with He–Xe lasers (40:1, 4 torr total pressure) with the setup shown in Fig. 2.

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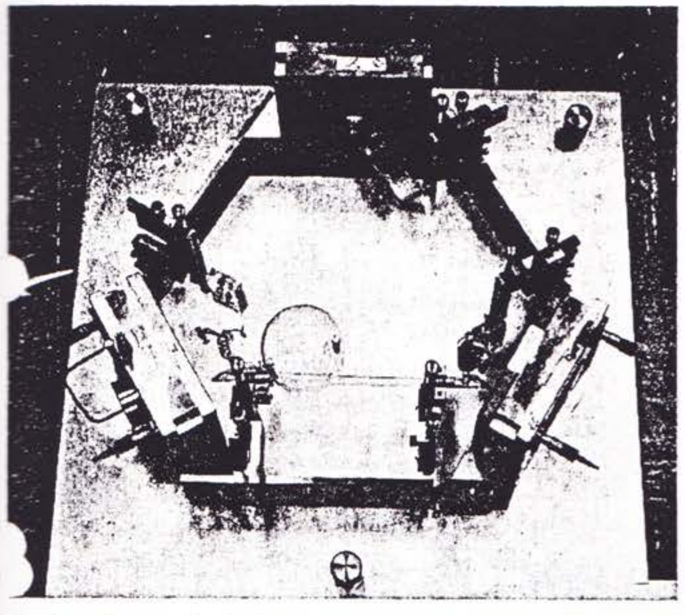

Fig. 3. Photograph of a ring-type cavity incorporating two confocal lenses and a He–Xe laser. This cavity is degenerate in the plane of the ring. The iris near the top mirror is used for preliminary alignments.

A. Gain, Bandwidth, and Transverse Mode Acceptance

The regenerative amplifier, shown in Fig. 3, makes use of a ring-type cavity comprised of three flat mirrors. One of them has a transmissivity of 25 percent to couple the beam in and out. Two identical stigmatic confocal lenses are incorporated. Let us analyze briefly the properties of this cavity. The round-trip ray matrix relative to the focusing elements is equal to −[1] in any meridional plane. The round-trip ray matrix relative to the three flat mirrors forming the ring is equal to −[1] in the ring plane and +[1] in the perpendicular plane [8]. In the ring plane the round-trip ray matrix is consequently equal to +[1] and any paraxial ray retraces its own path after a round trip. This is the condition for the cavity to be degenerate. In the perpendicular plane the round-trip ray matrix is equal to −[1], and it takes a paraxial ray 2 round trips to retrace its own path. The cavity is "half degenerate" in that plane. This peculiarity gives a convenient way of comparing the two situations.

The total path length of the ring is L = 960 mm corresponding to a free spectral range c/L = 310 MHz, and the focal lengths of the two lenses are $f = L/4$ = 240 mm. The cavity incorporates a 10-mm-ID He–Xe laser tube, with a discharge length of 180 mm, dc and RF excited (the RF excitation improves the stability).

The transmitter, set up on a separate table, generates a CW signal in the fundamental Gaussian mode with an electric field perpendicular to the ring plane. Optical attenuation is provided by calibrated glass plates. A fine adjustment in position of the incident beam with respect to the regenerative amplifier is provided by a couple of confocal lenses mounted on the same micromanipulator (translation of the incident beam being twice the lens system displacement). The position of the large receiver lens (focal length = 420 mm) is adjusted in order that the incident beam-waist radius ω_0 be equal to 0.26 mm at point F (see Fig. 2) where an iris is used for preliminary adjustments. F is close to the focuses of the cavity lenses. The beam-waist radius at the other focuses, near the middle of the laser tube, is consequently $\omega_0' = \lambda f/\pi\omega_0$ = 1 mm. A smaller value of the beam-waist radius in the laser medium would increase the harmful saturation effects.

The maximum gain and the bandwidth obtained with a constant output power of 0.7 μW, are given as a function of the laser single-pass gain in Fig. 4.

This figure shows that 24-dB gains and 1-MHz bandwidths can be obtained. Gains up to 37 dB and bandwidths as small as 0.14 MHz are observed by allowing the regenerative amplifier to oscillate with a small intensity. On the same Fig. 4 are shown the theoretical values obtained from (20) and (21), with r = 0.75 and g = laser power gain/2.95, where 2.95 represents the cavity loss. The discrepancy between the experimental and theoretical gain curves can be attributed to saturation effects in the laser medium.

In order to verify the degeneracy properties of the cavity, the incident beam axis is displaced before it enters the cavity. Fig. 5 shows that a displacement of ±1.3 mm in the ring plane where the cavity is degenerate does not reduce the gain by more than 4 dB. The ratio of the allowed transverse beam displacement to the beam-waist radius in that plane (equal to the ratio of the field of view to the far-field angle at the input lens) is consequently ±5.[2] In the direction perpendicular to the ring plane an expected [8] off-axis drop of the order of 3 dB is observed.

The cavity alignment is very critical in the ring plane where the cavity is degenerate [8]. The acceptable transverse displacement of a cavity lens in that plane is ±0.2 mm when the laser discharge is off and only ±0.025 mm when the laser discharge is on. In the direction perpendicular to the ring plane the corresponding values are, respectively, ±2.5 mm and ±0.5 mm.

B. Intermediate Frequency Response and Noise

The measurements reported in this section were made on a linear confocal cavity [11], which has the advantage of uncritical alignments. Such a cavity is "half degenerate" in any meridional plane and any incident on-axis Gaussian beam is automatically matched to it. For off-axis beams, however, half of the incident power is lost. The mirror separation, equal to the mirror radii, is 605 mm and the mirror reflectivity 0.8. The laser tube is the same as in the ring cavity. The gain and bandwidth obtained from this linear configuration are comparable to those of the ring-type cavity.

As shown in the block diagram in Fig. 2, the optical power is modulated by an RF voltage at 70 MHz applied to a crystal of lithium niobate (2 × 2 × 12 mm³). With

[2] For a fully degenerate cavity the accepted number of transverse modes would be of the order of $(5)^2$ = 25.

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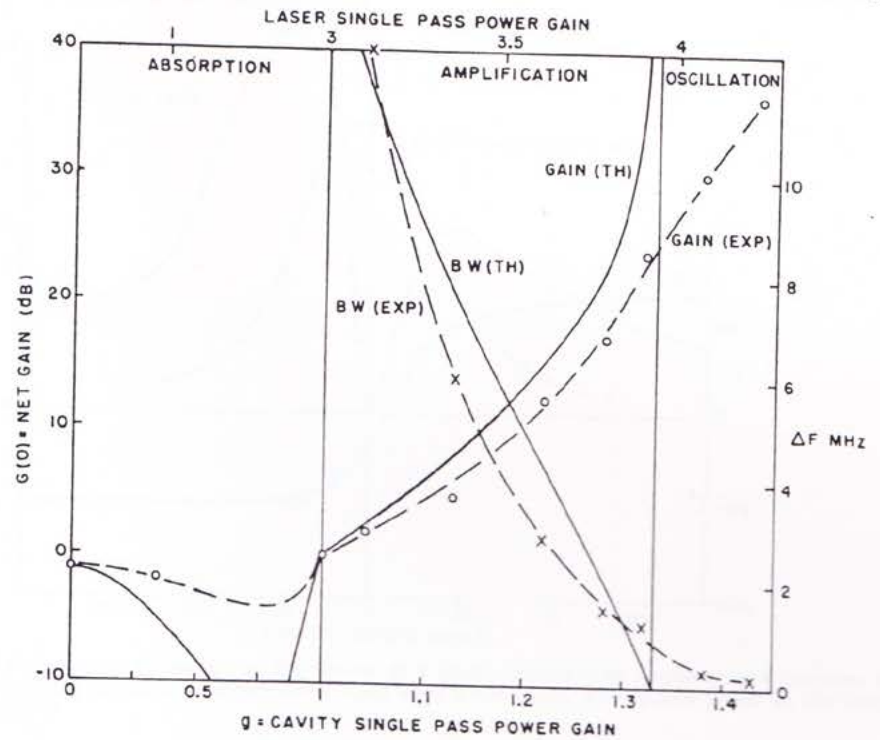

Fig. 4. This figure shows the measured gain and 3-dB bandwidth of a ring-type regenerative amplifier as a function of the single-pass laser gain and the results of the linear theory. The internal power loss of the cavity is 1/2.95. Notice that there is a change of scale at $g = 1$.

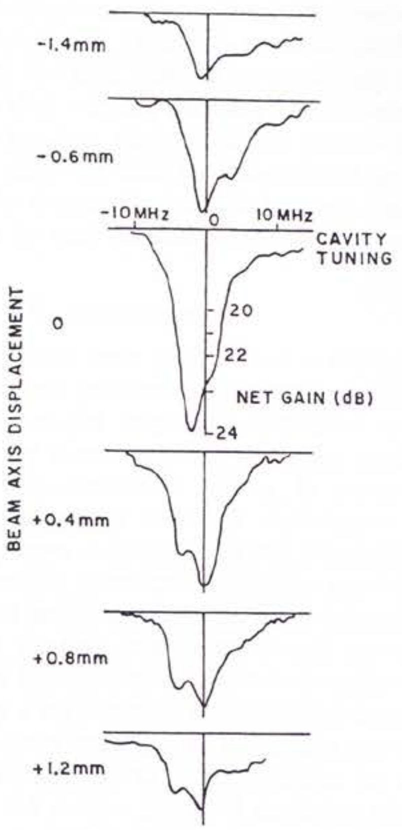

Fig. 5. Gain of the ring-type amplifier as a function of the cavity tuning for various positions of the input beam axis. The gain and frequency calibrations given on one of these curves apply as well to the others. The beam-waist radius is 0.26 mm.

the help of a polarizer an amplitude modulation is obtained. It is observed that the low-index frequency modulation introduced by the crystal is efficiently converted into an amplitude modulation because of the phase shift experienced by the carrier when the regenerative amplifier is slightly detuned. The discussion of Section II applies with little modifications to that case.

In the present linear configuration, the sidebands of the modulated optical signal are transmitted through the cavity (tuned at the carrier frequency) experiencing an attenuation of 13.4 dB. The IF response in amplitude and phase (with respect to the modulating voltage) and the optical power are shown as a function of the tuning in Fig. 6. When the regenerative amplifier is further detuned regenerative amplification is observed on either one of the two FM sidebands with a singly peaked IF response. Since the frequency separation between the sidebands and the carrier is precisely known, this provides a direct calibration of the cavity tuning.

In these measurements the amplifier output power is focused through a calcite polarizer and a 500-Å BW filter on a junction photodiode (Philco L4530) matched to the input of an IF amplifier. With a constant optical power of 0.65 μW and an rms IF detector current in the range 10^{-9} to 10^{-7} amperes, the IF signal power is proportional to the modulating power. The rms dark current shot noise, thermal noise, and optically induced noise, in agreement with the calculated values, are, respectively, 8×10^{-9}, 1.5×10^{-9}, and 4×10^{-10} amperes. The high dark current of the photodiode and the low optical power available in this experiment do not allow an accurate comparison between the different receiving schemes discussed in Section II.

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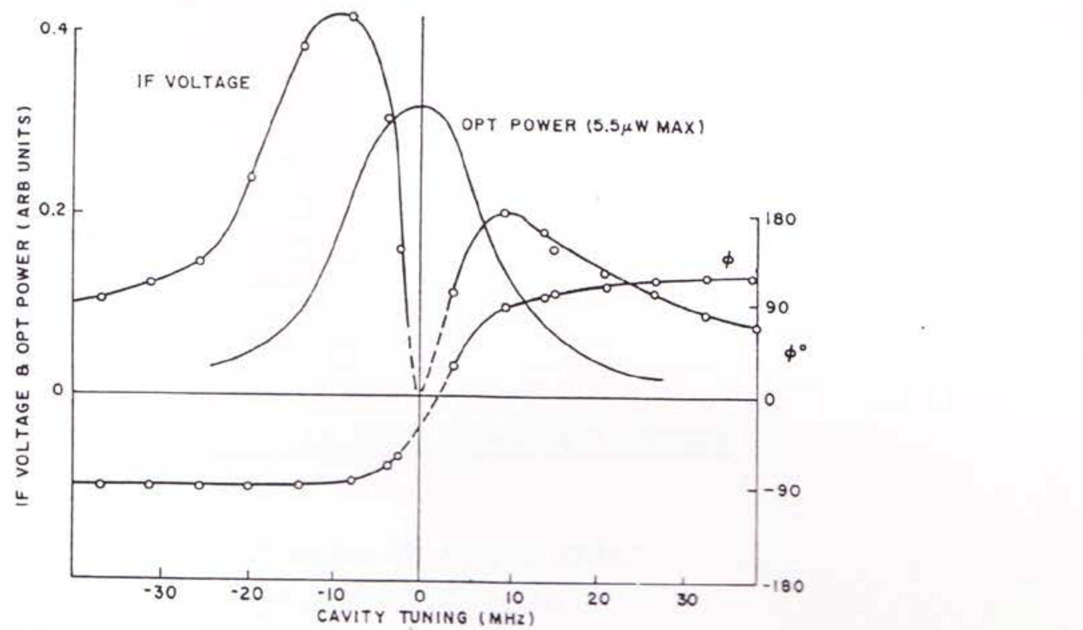

Fig. 6. Detected IF voltage and phase (Φ) at the output of a linear regenerative amplifier as a function of the cavity tuning. The incident signal is frequency-modulated with a low index. The optical power at the output of the amplifier is also given.

Acoustical and thermal protection of the cavities, although highly desirable, were not provided. The frequency locking system shown in Fig. 2 is able to track the oscillator frequency and keep the gain close to its maximum value during a period of time varying between 1 to 30 minutes depending on the incident power and the environment. Incidentally, it is observed that the laser discharge current drops by 1 per thousand when the incident beam is on. This effect can be used in place of a detector for frequency locking.

V. Conclusion

Simplified calculations have shown that a substantial improvement in optical receiver sensitivity can be expected if the carrier of the amplitude-modulated optical signal is amplified by a narrow-band quantum amplifier before detection. This conclusion applies, in particular, to the case of signals with distorted wavefronts. Experiments at 3.5 μ have demonstrated the feasibility of degenerate regenerative quantum amplifiers capable of amplifying distorted wavefront signals, with large gains and narrow bands. Further improvements are necessary in order to increase the number of transverse modes that can be amplified by a regenerative amplifier and accepted by a fast response detector. The low saturation power in HeXe (70 $\mu W/mm^2$) appears to be a limitation for optimum operation at 3.5 μ. The proposed receiving scheme seems to be particularly suitable for communications at 10.6 μ (CO_2 laser) through clear but possibly turbulent atmosphere.

Acknowledgment

In Section II the author freely used calculations made by R. Kompfner relative to the closely related "pilot scheme" that he originally proposed. The author expresses his thanks to R. Kompfner, D. C. Hogg, L. C. Tillotson, and H. E. Rowe for their interest in this work and many helpful suggestions, and to W. J. Kluver and R. W. Wilson who gave him valuable advice in the experimental work.

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