END
DATE
FILMED
'1 -82
DTIC

013
DTI Center

NOTICE

This report was prepared as an account of work
sponsored by the United States Government. Neither
the United States nor the Naval Research Laboratory,
nor any of their employees, nor any of their contractors,
subcontractors, or their employees, makes any warranty,
express or implied, or assumes any legal liability or
responsibility for the accuracy, completeness or
usefulness of any information, apparatus, product or
process disclosed, or represents that its use would not
infringe privately owned rights.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER N00014-81-C-2412	2 GOVT ACCESSION NO. AD-A107 743	3 RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 1 GHz Bandwidth Recirulating Optical Analog Repeater		5 TYPE OF REPORT & PERIOD COVERED Final Report JUL 81-NOV 81
		6. PERFORMING ORG. REPORT NUMBER
7 AUTHOR(s) T.V. Muoi		8 CONTRACT OR GRANT NUMBER(s) N00014-81-C-2412
9. PERFORMING ORGANIZATION NAME AND ADDRESS TRW Technology Research Center 2525 E. El Segundo Boulevard El Segundo, California 90245		10 PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS NAVAL RESEARCH LABORATORY WASHINGTON, D.C. 20375		12 REPORT DATE NOVEMBER 1981
		13. NUMBER OF PAGES 39 Pages
14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

- Recirculating Repeater

- Wideband Analog Repeater

- Fiber Optic Delay Line

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Theoretical performance of a 1 GHz bandwidth recirculating analog repeater for use as a fiber optic delay line is investigated. Noise and harmonic distortion due to the photodetector and fiber-coupled laser are analyzed in detail. It was shown that for an output signal-to-noise and signal-to-distortion ratio of 25 dB, a delay time of the order of 1 millisecond can be achieved.

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
1 JAN 73

Forward by S.D. Personick

The following report is the output of an analysis of the fundamental and practical limitations on the performance of a recirculating fiber optic delay line with a large delay-bandwidth product.

We perceive the desired bandwidth to be in excess of 1 GHz and the desired delay to be in excess of 1 ms.

As shown in the analysis, such performance is possible; but not achievable with existing technology, - except for very low signal-to-noise ratio requirements at the delay line output (less than 25 dB). This is a consequence of the required power at the receiver input (a fundamental limitation) even for a very sensitive receiver employing a detector with "silicon like" gain statistics; and also a consequence of practical limitations involving modal noise and modal distortion.

However, such performance might be achievable at moderate signal-to-noise ratios (more than 35 dB) if one could develop a long wavelength laser transmitter with a stable single longitudinal mode, capable of 1 GHz modulation, with an output power into a single mode fiber in excess of 5 mW. The exact requirements could be specified if more were known of the precise delay and signal-to-noise/signal-to-distortion requirements. Such a transmitter might be implemented using integrated optics techniques; to combine an external cavity laser with an electro-optic modulator.

Additionally, to achieve the perceived performance requirements one would require a low loss (0.5 dB or less) single mode fiber with a well controlled minimum dispersion wavelength and with very low birefringence (or a fiber which is polarization preserving). Further one must demonstrate a low noise, 1 GHz (flat) bandwidth, receiver with a silicon like APD detector. Recent reports on the performance of a HgCdTe detector look very promising in this regard.

i

TABLE OF CONTENTS

ii

1.0 INTRODUCTION

This report is the final report of a four month analytical study of the feasibility of a 1 GHz bandwidth recirculating optical analog repeater designed for use in an optical delay line. The study was conducted at the TRW Technology Research Center and completed in November 1981. This research was sponsored by the Naval Research Laboratory under Contract Number N00014-81-C-2412.

This report is concerned with the theoretical investigation of the feasibility of a 1 GHz Bandwidth Recirculating Optical Analog Repeater. The function of this recirculating repeater is to serve as part of an optical delay line. In this delay line, an electrical pulse having 1 GHz bandwidth is injected into the transmitter of the recirculating repeater at time t_o. The optical output pulse from the repeater is launched into a fiber of length L and delay T_f. The fiber output pulse re-enters the recirculating analog repeater and is detected, amplified and transmitted through the fiber again. Finally, after n passes through the recirculating repeater, the delayed electrical pulse is recovered from the receiver of the recirculating repeater. The total delay time obtained is thus nT_f. In this report, we will investigate the requirements on the transmitter and receiver of the recirculating analog repeater and the maximum total delay that can be obtained.

The design for a low noise receiver amplifier with 1 GHz bandwidth suitable for use in the recirculating repeater is reported in Section 2. A complete system analysis for the recirculating repeater is presented in Section 3. Both signal-to-noise ratio and harmonic distortion constraints are considered. System design aspects are presented in Section 4. Laser characteristics required for the repeater performance are considered. Two examples of the recirculating repeater design are given: a "moderate quality" repeater with 25 dB signal-to-noise and signal-to-distortion ratio, and a "high quality" repeater with 35 dB signal-to-noise and distortion ratio. Finally, in Section 5, we discuss in detail further sources of noise and distortion that can occur due to the interaction between the laser and the coupled optical fiber.

2.0 RECEIVER AMPLIFIER DESIGN

In order to obtain the maximum delay time in passing through the
recirculating repeater, the receiver has to be as sensitive as possible.
This section is concerned with the design of a low noise receiver amplifier
suitable for use in the recirculating repeater. Since it is required
that the system bandwidth is 1 GHz after ten passes through the recirculating
repeater, the receiver amplifier frequency response has to be flat to
1 GHz. In addition, it should be noted that the flatness of the receiver
frequency response is very important since any ripple would tend to
be magnified by the number of passes.

The receiver amplifier was designed by using two computer-aided
design programs: "COMPACT" for optimizing the amplifier frequency response
and "SPICE" for verifying its noise level. Because of the high frequencies
involved, the transistors are characterized by measuring their s- parameters,
at the operating bias conditions, to 1.3 GHz. These measured characteristics
are used in the CAD transistor modeling.

A schematic of the low-noise wide-band receiver amplifier is shown
in Figure 1. The amplifier configuration is based on the design technique
of mismatching interstage coupling so that the effects of stray capacitances
are minimized. The first stage Q_1 is a shunt-feedback transimpedance stage
while the second stage Q_2 has the series-feedback configuration, with its
output impedance well-matched to the 50 ohm load impedance. Both
transistors are silicon microwave bipolar transistors (AK4690) with cut
off frequency f_T of about 8 GHz. The final circuit element values are
obtained by optimizing the amplifier frequency response using COMPACT.
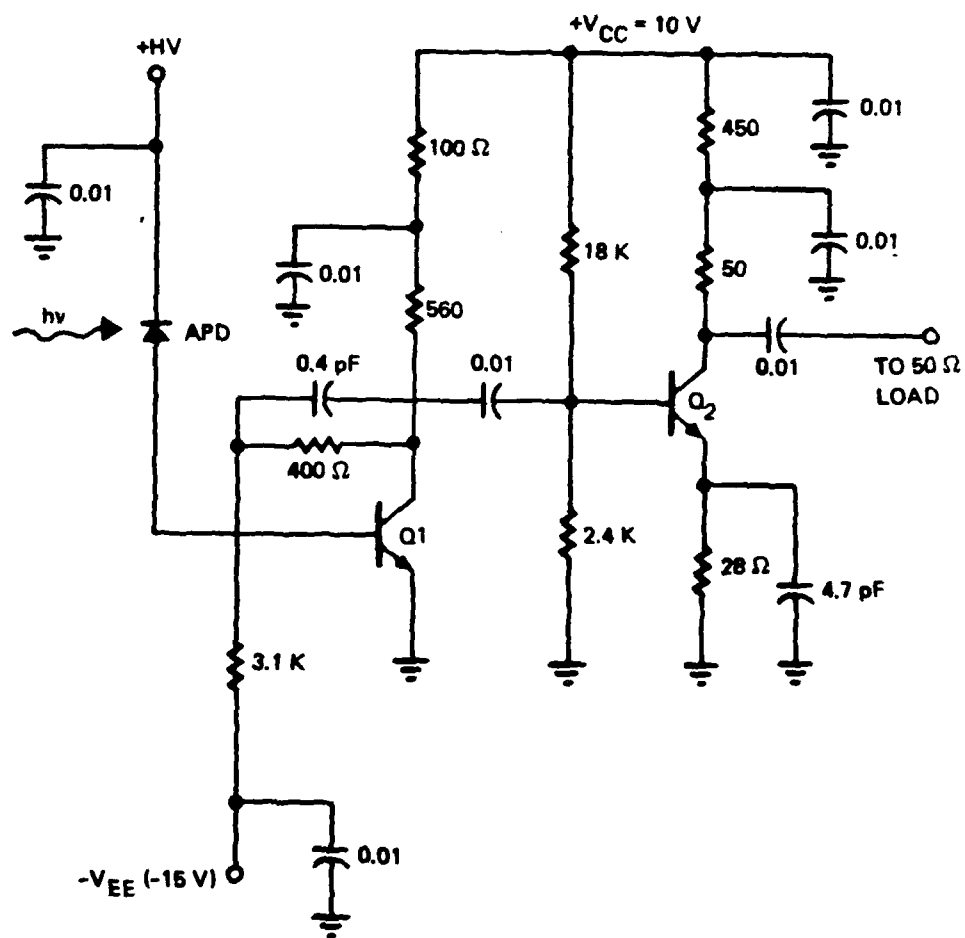The CAD-simulated frequency response is shown in Figure 2.

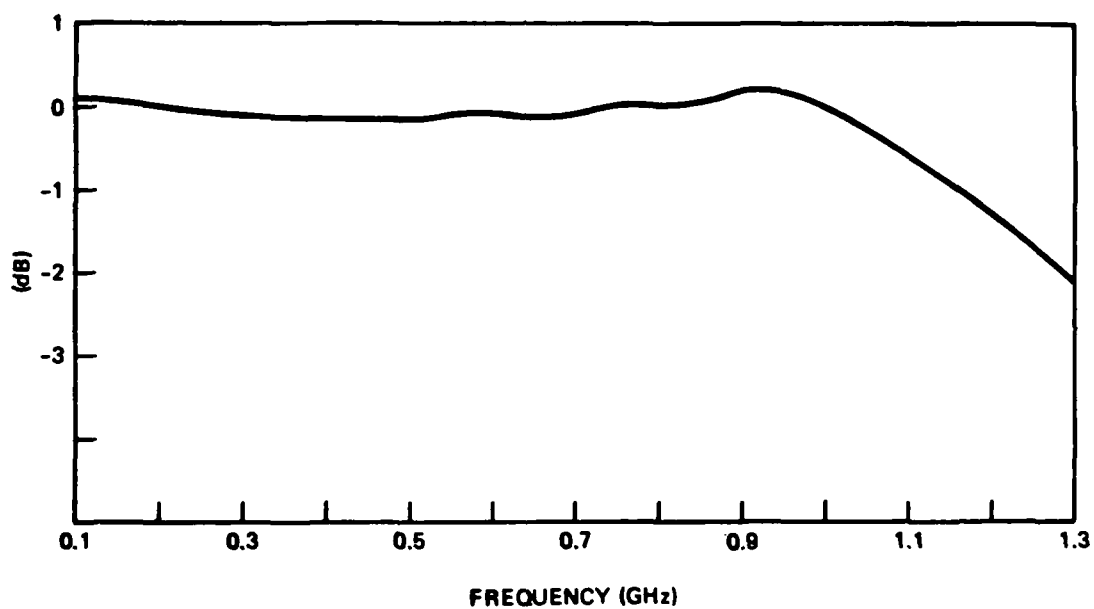Figure 1.   Receiver Amplifier Schematic

Figure 2. Simulated frequency response of receiver amplifier.

The input equivalent noise spectral density of the transimpedance receiver amplifier is given by [1,2,3]:

$$N(f) = \frac{4kT}{R_f} + 2qI_b + \frac{2q}{I_c}\left(2\pi C_T V_T\right)^2 f^2 + 4kTr_{bb'}\left(2\pi C_d\right)^2 f^2 \qquad (1)$$

where R_f is the feedback resistance,

I_b, I_c are the transistor base and collector bias currents,

C_T is the total capacitance at the amplifier input,

C_{ds} is the photodiode capacitance (including stray capacitance),

$r_{bb'}$ is the transistor base-spreading resistance,

and

$V_T = kT/q$.

The first two terms in the above equation are due to the feedback resistor thermal noise and base current shot noise and are frequency-independent. The last two terms are due to the collector current shot noise and base resistor thermal noise and increase with frequency as f^2.

The total equivalent input noise power in a given bandwidth B can can be obtained by integrating equation (1). There exists a collector bias current which minimizes this noise power [2,3]. Using the measured parameters in our application, the optimum collector bias current is calculated to be approximately 3mA. In order to avoid any potential decrease in f_T and β of the transistor at low currents, the final bias current is chosen at 6 mA. At this bias point, the amplifier noise level is increased by less than 0.5 dB, which has a negligible effect on the receiver sensitivty.

[1] J.L. Hullett & T.V. Muoi, "A Feedback Receiver Amplifier for Optical Transmission Systems", IEEE Trans. Comm., COM-24, Oct. 1976 pp 1180-1185.

[2] R.G. Smith & S.D. Personick, "Receiver Design for Optical Fiber Communication Systems", Chp. 4 in Semiconductor Devices for Optical Communication, Springer-Verlag, 1980.

[3] J.E. Goell, "Input Amplifiers for Optical PCM Receivers", BSTJ, Vol 53, Nov. 1974, pp 1771-1793.

The equivalent input noise spectral density of the amplifier
is shown in Figure 3. The straight lines in the figure correspond to
the terms in equation (1), while the curves are actual values obtained
from the SPICE program. The total noise predicted by SPICE is slightly
higher than equation (1) due to other circuit elements (bias resistors
and Q_2). The equivalent noise resistance is also shown on the right hand
side scale of Figure 3.

The equivalent noise resistance in a 1 GHz bandwidth is calculated
to be 100 ohms. This value will be used for system analysis in the
remainder of this report. In addition, a more moderate value of 50 ohms
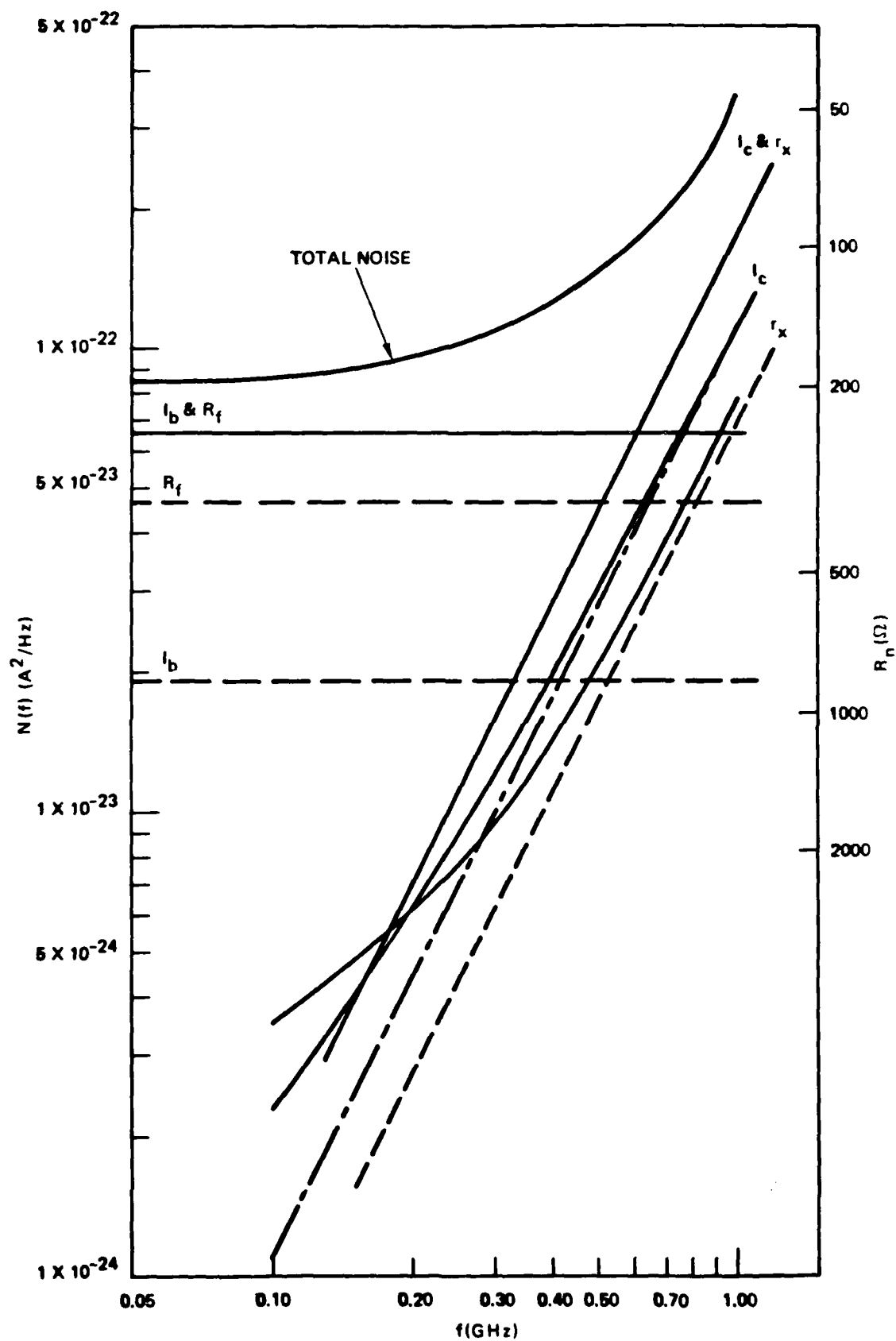equivalent noise resistance is also included for comparison.

Figure 3. Noise sources of receiver amplifier.

3.0 SYSTEM ANALYSIS

A block diagram of the system is shown in Figure 4. Input signal $x(t)$ modulates the laser optical power with modulation index m_o:

$$P_T(t) = P_L \left[1 + m_o x(t) \right] \qquad (2)$$

where P_L is the average output power of the laser. The detected current at the receiver output is given by:

$$i(t) = L_f AGRP_L m_o x \left(t - T_f \right) \qquad (3)$$

where L_f is the fiber loss, G is the avalanche gain, R is the primary responsivity of the photodiode, A is the receiver gain, and T_f is the delay through the fiber length. This detected current is fed back to modulate the laser. The loop gain of the system is therefore given by:

$$\beta = EL_f AGR \qquad (4a)$$

where E is the slope of the laser optical power versus current characteristic (watt/amp).

It can be seen that the modulation index after one pass through the the repeater becomes:

$$m_1 = \beta m_o \qquad (4b)$$

Therefore the modulation index after n passes through the recirculating repeater is given by:

$$m_n = \beta^n m_o \qquad (5)$$

For stability, it is required that $\beta < 1$. This results in a decreasing modulation index on each pass around the loop.
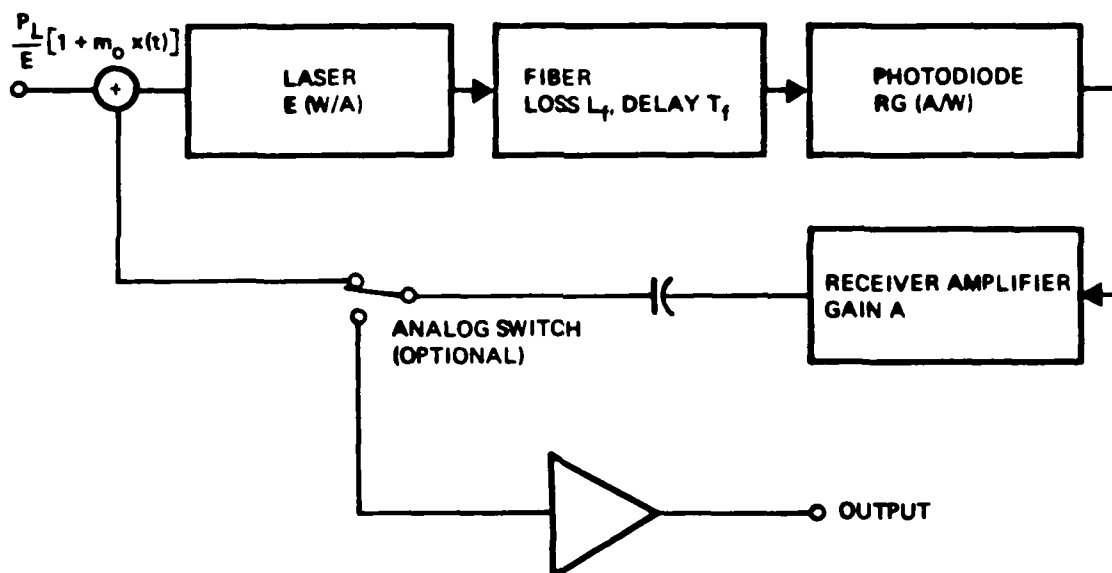
$$\frac{P_L}{E}[1 + m_o\, x(t)]$$

LASER
E (W/A)

FIBER
LOSS L_f, DELAY T_f

PHOTODIODE
RG (A/W)

RECEIVER AMPLIFIER
GAIN A

ANALOG SWITCH
(OPTIONAL)

OUTPUT

Figure 4.   Block diagram of recirculating repeater.

3.1 SIGNAL-TO-NOISE-RATIO

Let the input optical power to the receiver be of the form:

$$P_r(t) = \overline{P}\left\{1 + m\left[\sin\omega t + n_i(t)\right]\right\} \tag{6}$$

where $\overline{P}$ is the average received power, m is the modulation index and $n_i(t)$ is the noise term of the received optical signal. The input signal-to-noise ratio (SNR), which is defined here as the ratio of peak signal and rms noise power, is given by:

$$\left(\frac{S}{N}\right)_{in} = \frac{1}{\overline{n_i^2}} \tag{7}$$

The detected photo-current signal is given by:

$$<i(t)> = RG\overline{P}m\sin\omega t \tag{8}$$

The noise power of the detected current can be shown to be:

$$<i^2(t)> = (RG\overline{P}m)^2\overline{n_i^2} + n_a^2 + 2qR\overline{P}<G^2>B \tag{9}$$

where n_a^2 is the amplifier noise term and B is the system bandwidth.

The (peak) output signal-to-noise ratio is therefore:

$$\frac{S}{N}\text{ out} = \frac{(RG\overline{P}m)^2}{(RG\overline{P}m)^2\overline{n_i^2} + n_a^2 + 2qR\overline{P}<G^2>B} \tag{10}$$

We thus now have obtained an equation relating the input and output SNR after one pass through the repeater.

$$\left(\frac{N}{S}\right)_{out} = \left(\frac{N}{S}\right)_{in} + \frac{n_a^2 + 2qR\overline{P}<G^2>B}{(RG\overline{P}m)^2} \tag{11}$$

Assuming that the laser noise is not significant (laser noise will be discussed in later sections), the output noise-to-signal ratio after the first pass is given by:

$$\left(\frac{N}{S}\right)_1 = \frac{n_a^2 + 2qR\overline{P}<G^2>B}{\left(R\overline{P}Gm_0\right)^2} \tag{12}$$

The output noise-to-signal ratio after two passes is:

$$\left(\frac{N}{S}\right)_2 = \frac{n_a^2 + 2qR\overline{P}<G^2>B}{(R\overline{P}G)^2}\left(\frac{1}{m_0^2} + \frac{1}{m_1^2}\right) \tag{13}$$

Therefore, it can be shown that the noise-to-signal ratio after n passes is given by:

$$\left(\frac{N}{S}\right)_n = \frac{n_a^2 + 2qR\overline{P}<G^2>B}{(R\overline{P}G)^2}\left(\frac{1}{m_0^2} + \frac{1}{m_1^2} + \cdots + \frac{1}{m_{n-1}^2}\right) \tag{14}$$

By using equation (5) it can be shown that:

$$\left(\frac{N}{S}\right)_n = \frac{n_a^2 + 2qR\overline{P}<G^2>B}{\left(R\overline{P}Gm_0\right)} \cdot \frac{\beta^{-2n} - 1}{\beta^{-2} - 1} \tag{15}$$

Therefore, the degradation in SNR after n passes through the recirculating repeater is given by:

$$\left(\frac{S}{N}\right)_n \Big/ \left(\frac{S}{N}\right)_1 = (\beta^{-2} - 1)/(\beta^{-2n} - 1) \tag{16}$$

This SNR degradation is plotted in Figure 5 as a function of β for up to 10 passes through the loop. It can be seen that as the loop loss increases, the SNR degradation increases because of a smaller modulation index. A value of 1 dB for loop loss is reasonable in order to avoid loop instability problems,
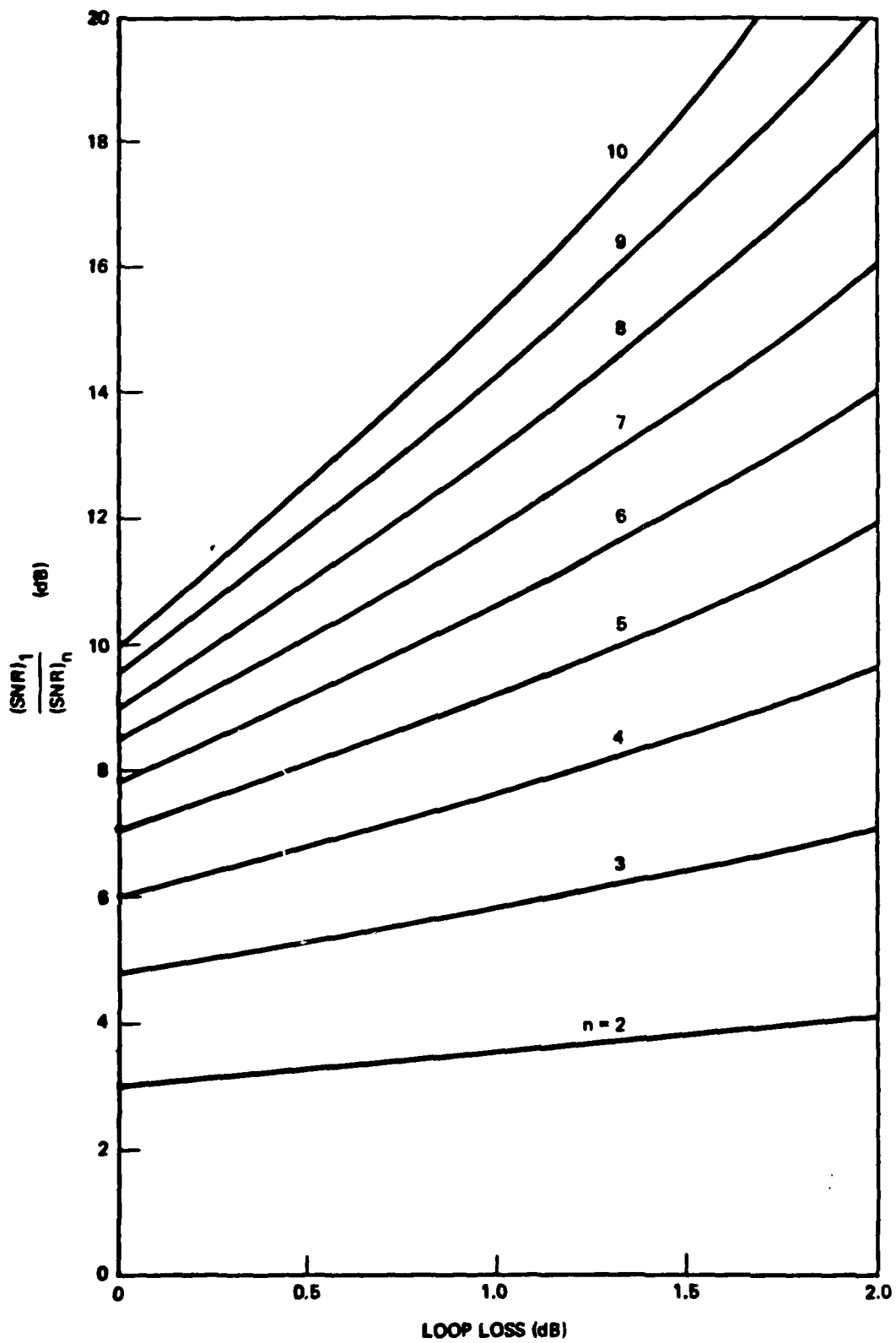
-11-

Figure 5. Signal-to-noise degradation versus loop loss.

yet is low enough to keep the SNR degradation small. It can be
seen from Figure 5 that after 10 passes, a 1 dB loop loss increases
the SNR degradation from 10 dB (for an ideal zero dB loop loss) to
15.4 dB.

3.2 REQUIRED OPTICAL POWER

It has been shown that when the final SNR at the recirculating
repeater is specified, Figure 5 can be used to determine the required
SNR_1 after the first pass through the loop. From this condition,
the input optical power required at the receiver can be determined.
Solving equation (12) for $\overline{P}$, we obtain the following expression for
the detected optical power required.

$$\eta\overline{P} = \frac{h\Omega}{m_0^2} BF(G)\left(\frac{S}{N}\right)_1 \left[1 + \sqrt{1 + \frac{n_a^2 m_0^2}{[qBF(G)G]^2}\left(\frac{N}{S}\right)_1}\right] \tag{17}$$

where $F(G)$ is the avalanche gain excess noise given by [4]:

$$F(G) = kG + (2 - 1/G)(1 - k) \tag{18}$$

with k being the ionization constant ratio of the APD. If a p-i-n
photodiode is used, equation (17) is also applicable by letting
$G = F(G) = 1$.

The detected optical power required is plotted in Figure 6
as a function of the single pass SNR_1. An initial modulation index
$m_0 = 0.5$ is assumed. The required optical power is calculated for
two different input equivalent noise resistances of the receiver
amplifier: 50 ohms and 100 ohms. Both p-i-n and avalanche photodiodes
are shown for comparison. Three different APD's are considered:

[4] R.J. McIntyre, "Multiplication Noise in Uniform Avalanche Junctions",
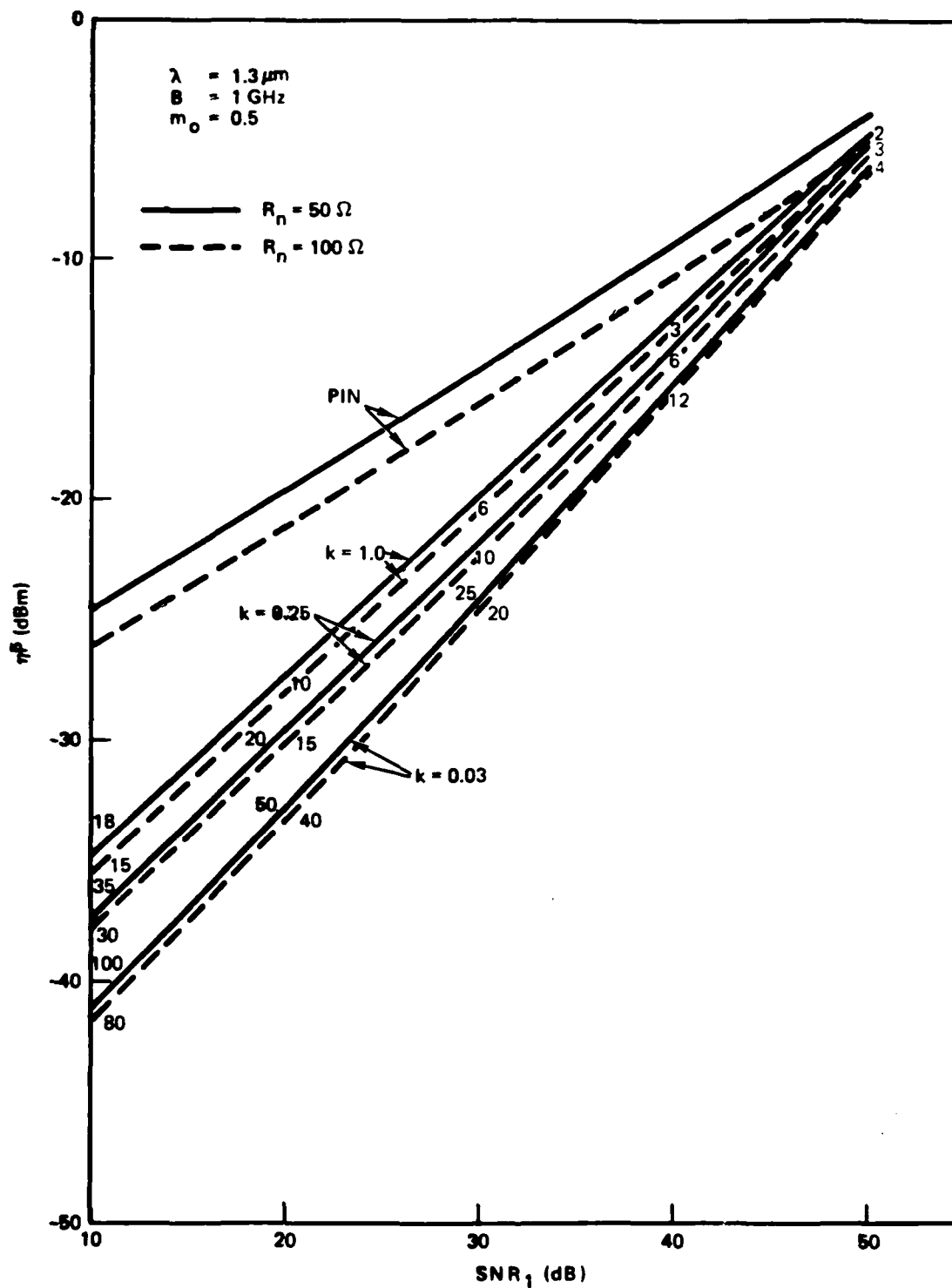   IEEE Trans. Elec. Dev., ED-13, Jan. 1966, pp 164-168.

Figure 6.   Required detected optical power versus SNR_1.

a Germanium APD (k = 1.0), a typical GaInAs or GaInAsP APD (k = 0.25)
[5] and an optimistic "silicon-like" APD for 1.3 μm (k = 0.03).
It is noted here that initial results reported for such a high
performance APD using HgCdTe devices are very promising [6]. In all
cases, the APD dark current effect on the required power is negligible
if the primary dark current is less than the required power shown
(in watts) multiplied by the conversion factor 0.8 A/W. For example,
for SNR_1>15 dB, a primary dark current of 100 nA can be neglected
even for the most sensitive receiver shown. The numbers along the
curves for the APD receivers represent the optimum avalanche gain
required.

It can be seen from Figure 6 that if the required single pass
SNR_1 is low (20 to 30 dB), the APD receivers are more sensitive than
the p-i-n receiver. The optimum avalanche gains required are also
in the medium range (10 to 50) which is reasonably stable. However,
when the required SNR is high, (approaching 50 dB), the required
optimum gain drops to 2 to 4 and the advantage of the APD over the
p-i-n photodiode is lost.

It should be realized that the full advantage of the APD over
the p-i-n receiver as shown in Figure 5 may not be fully realized.
Because of possible APD gain variation, the loop loss in the APD
repeater may have to be higher to insure system stability. As
seen from Figure 5, this would lead to an increase in the SNR
degradation and hence an increase in the required single pass SNR_1.

The effects of initial modulation index m_o on the required
optical power can be seen from Figures 7,8, and 9. In these
figures, an amplifier noise resistance of 50 ohms is assumed.
The single pass SNR_1 are taken to be 30 dB, 40 dB and 50 dB respectively.
It can be seen that as the initial modulation index is decreased,
the required optical power increases at different rates, depending
on whether a p-i-n or an APD detector is used.

[5] T.P. Pearsall, "Photodetectors for Optical Communication", Jour. Opt.
Comm., Vol 2, June 1981, pp 42-48.

[6] J. Meslage et al, "Fast, High Gain 1.3 μm HgCdTe Photodiode", Proc. 7th
ECOC, Copenhagen, Sept. 1981, paper 11.4

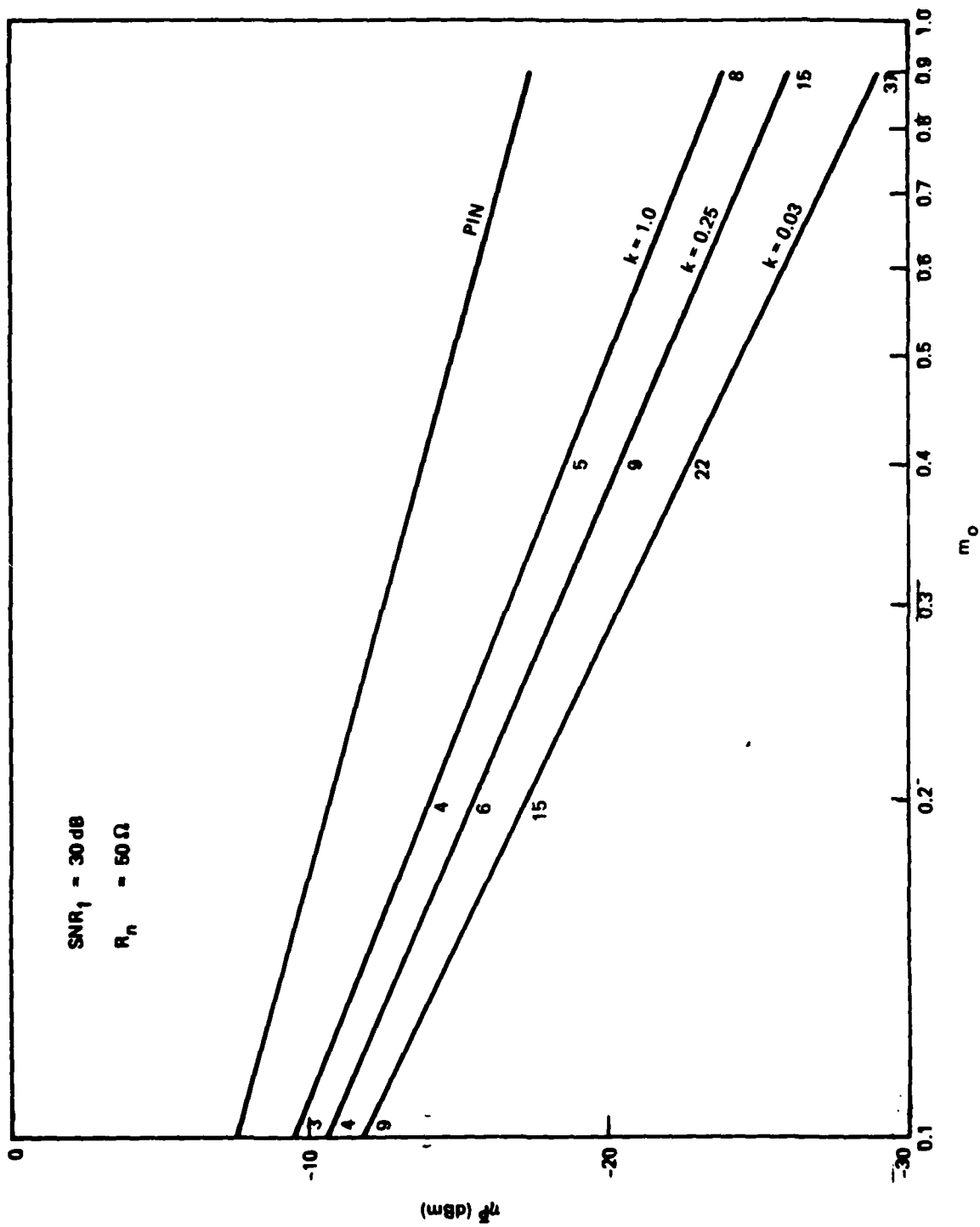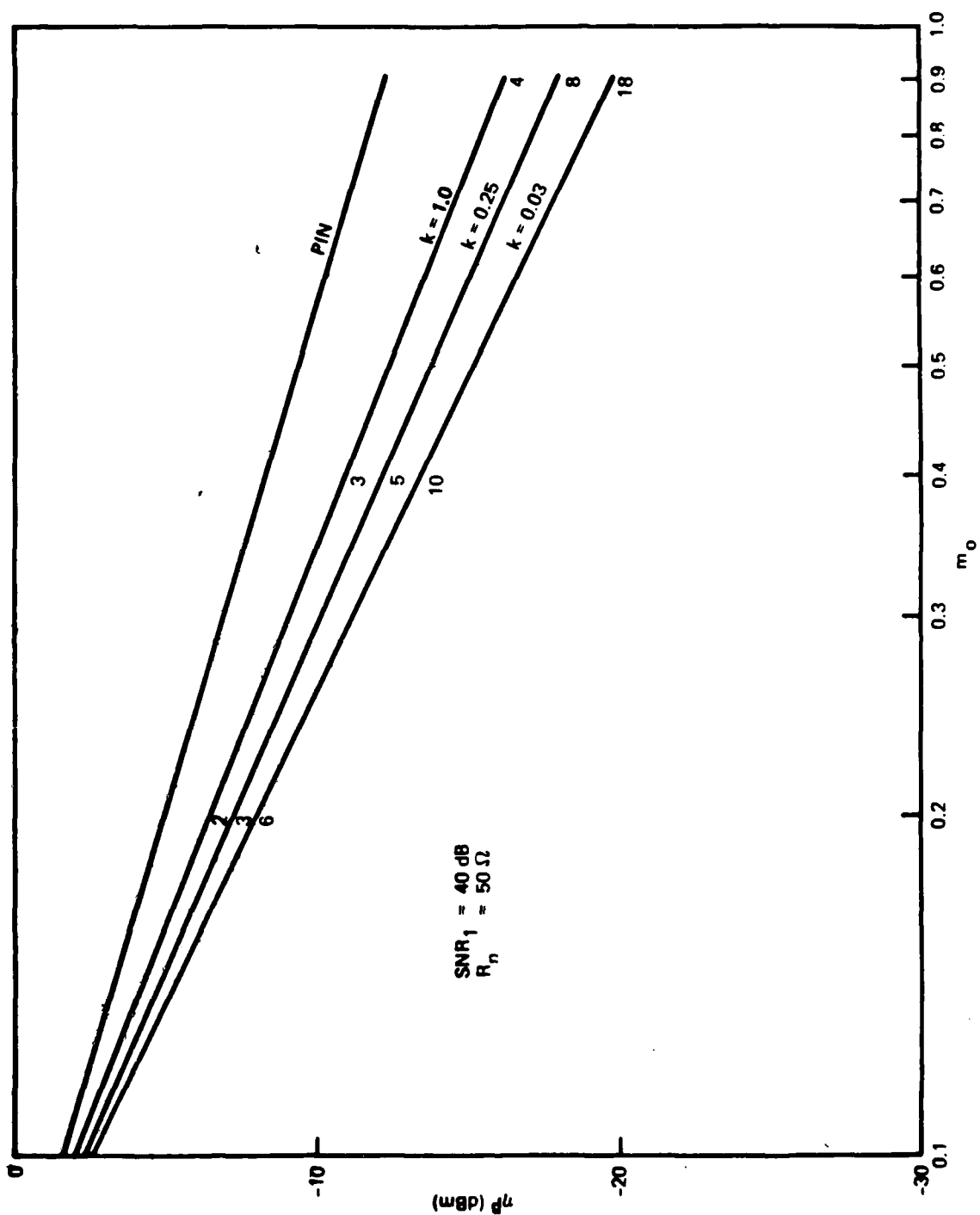Figure 7. Required detected optical power versus m_0 for SNR_1 = 30 dB.

-16-

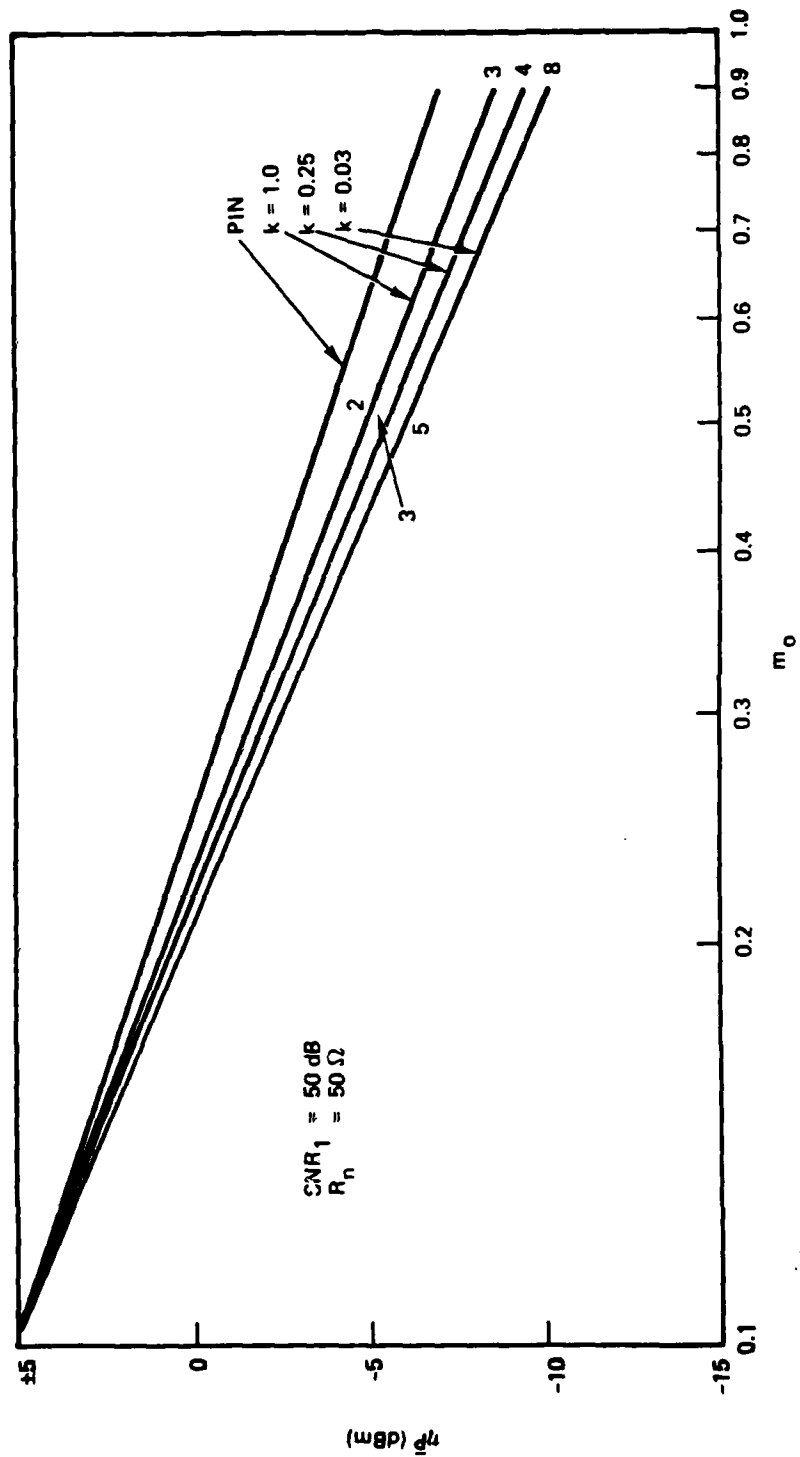Figure 8. Required detected optical power versus m_o for SNR_1 = 40 dB.

Figure 9. Required detected optical power versus m_o for SNR_1 = 50 dB.

3.3 HARMONIC DISTORTION

As the signal recirculates through the repeater, the harmonic distortion increases. In this section, expressions for the signal-to-distortion ratio are developed.

Let the transfer curve relating the output e_o to the input e_i of the system be (the linear gain factor is normalized):

$$e_o = e_i + a_2 e_i^2 + a_3 e_i^3 \qquad (19)$$

The input signal can be written as:

$$e_i = m\overline{P} \cos \omega t \qquad (20)$$

where m is the modulation index. Substituting this into equation (19), we obtain the following expressions for the second and thrid harmonic distortion:

$$2HD = \frac{a_2}{2} m\overline{P} \qquad (21)$$

$$3HD = \frac{a_3}{4} (m\overline{P})^2 \qquad (22)$$

From these equations, we have derived that the harmonic distortions after n passes through the repeater are given by:

$$(2HD)_n = \frac{a_2}{2} \overline{P} \left(m_0 + m_1 + \cdots + m_{n-1} \right) \qquad (23)$$

$$(3HD)_n = \frac{a_3}{4} \overline{P}^2 \left(m_0^2 + m_1^2 + \cdots + m_{n-1}^2 \right) \qquad (24)$$

By using equation (5) we can express the final harmonic distortions after n passes to the initial values after one pass as:

$$\frac{(2HD)_n}{(2HD)_1} = \frac{1-\beta^n}{1-\beta} \qquad (25)$$

and

$$\frac{(3HD)_n}{(3HD)_1} = \frac{1-\beta^{2n}}{1-\beta^2} \qquad (26)$$

These harmonic distortion degradations are plotted in Figures 10 and 11 as functions of the loop loss for up to 10 passes through the repeater. It can be seen that as far as distortion is concerned, a high value of loop loss is desirable since this would result in a decreasing modulation index when the signal passes round the loop. At a loop loss of 1 dB, the second and third harmonic distortions after 10 passes are 16 dB and 12.8 dB worse than a single pass.
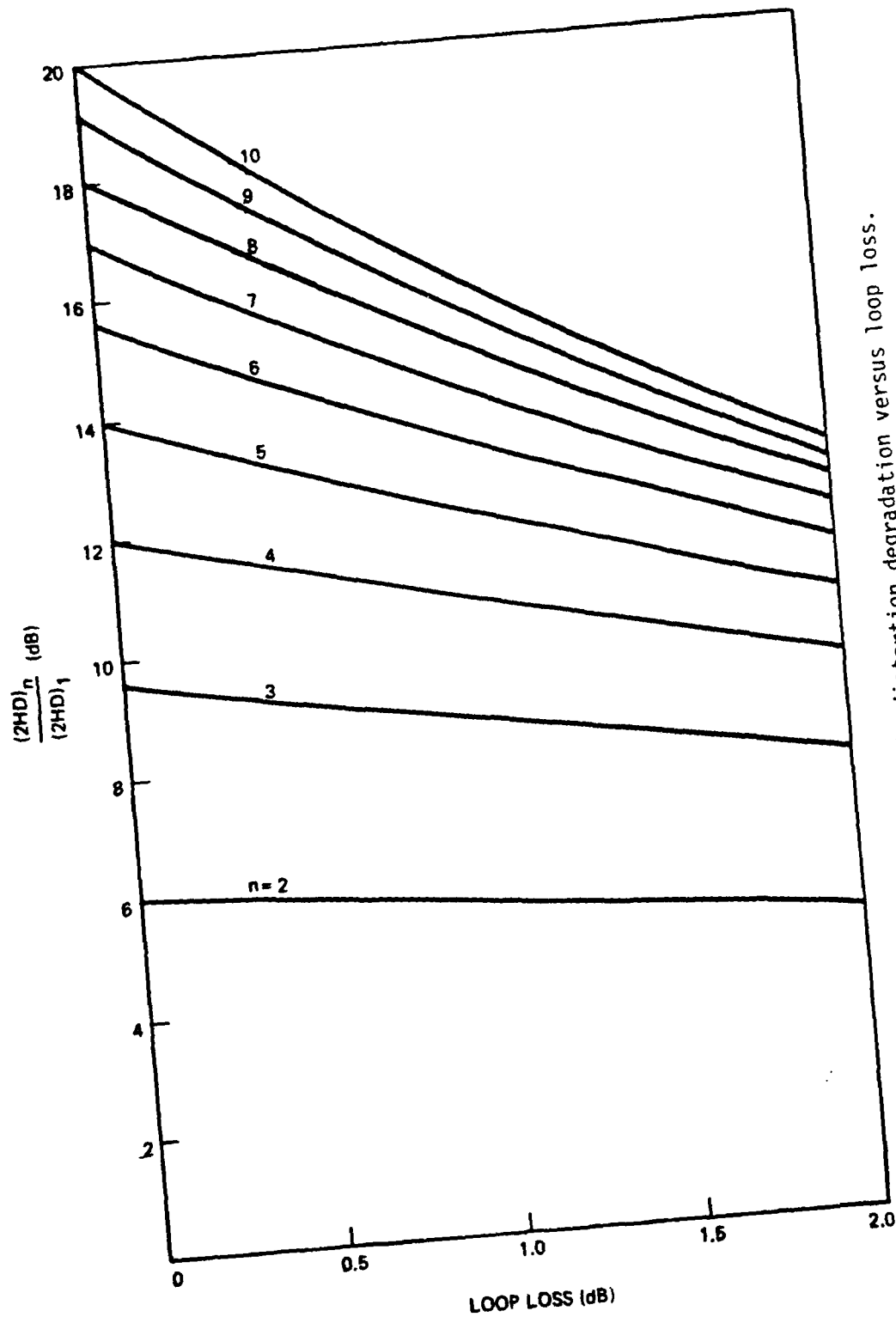
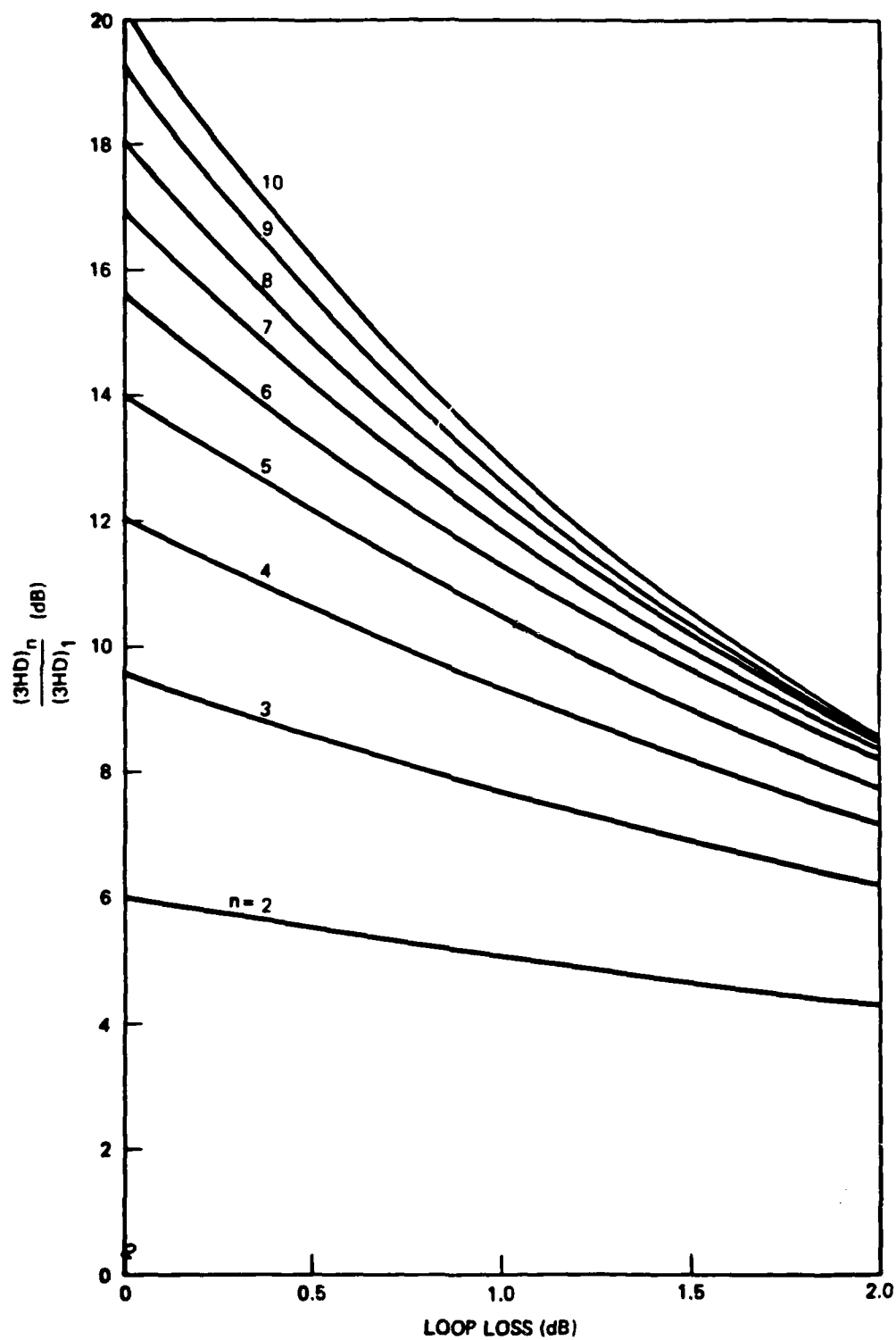Figure 10. Second harmonic distortion degradation versus loop loss.

Figure 11.   Third harmonic distortion degradation
versus loop loss.

4.0 SYSTEM DESIGN

We now consider the design of the recirculating repeater to obtain the maximum delay time possible. The laser characteristics used in the transmitter are important since they dictate the system harmonic distortions and put an upper limit in the maximum achievable signal-to-noise ratio.

4.1 LASER CHARACTERISTICS

In this section, we consider the intrinsic characteristics of the laser. Any subtle noise and distortion due to its interaction with the coupled fiber will be discussed separately later.

The system harmonic distortion is dominated by the laser non-linearity. This is most important for wide-band systems since laser harmonic distortion increases with frequency. Laser distortion has been analyzed theoretically and measured experimentally [7,8,9,10]. To obtain good linear characteristics, lasers have to be biased well above threshold. Based on the results reported, a reasonable specification for the laser linearity which can be met at reasonable yield is as follows:

$$
\left.
\begin{array}{l}
2 \text{ HD} < -40 \text{ dB} \\
\\
3 \text{ HD} < -50 \text{ dB}
\end{array}
\right\}
\quad
\begin{array}{l}
\text{Measured at } f = 500 \text{ MHz} \\
\text{at 0.5 modulation index}
\end{array}
$$

The above specifications are also consistent with GaAlAs lasers available commercially. It is expected that 1.3 μm lasers should achieve the same performance.

[7] K. Stubkjaer et al, "Nonlinearities of GaAlAs Lasers - Harmonic Distortion", IEEE Jour. Quant. Elec., QE-16, May 1980, pp 531-537.

[8] M. Maeda et al, "Harmonic Distortions in Semiconductor Injections Lasers", Proceed. 5th ECOC, Sept. 1979, Paper 18.5.

[9] K. Nagano et al, "Optimizing Optical Transmitters and Receivers for Transmitting Multichannel Video Signals Using Laser Diodes", IEEE Trans. Comm., COM-29, Jan. 1981, pp 41-45.

[10] G. Grobkopf et al, "Measurement of Non-linear Distortion in Index- and Gain-Guiding GaAlAs Lasers", Jour. Opt. Comm, Vol. 1, Sept. 1980, pp15-17.

The other important characteristic of the laser is its intrinsic quantum noise, since it puts an upper bound on the maximum SNR. This laser noise is more important for wideband high quality systems. The intrinsic laser noise level has been evaluated [11,12]. The dc signal-to-noise ratio of good lasers have beem measured at 150 dB/Hz. This noise level is assumed here and its impact on the system performance will be considered.

Finally, the amount of average optical power that can be coupled to a single mode fiber is taken to be -3 dBm. The laser modulation bandwidth has, of course, to be greater than 1 GHz.

4.2 MODERATE QUALITY REPEATER

In this section we consider the design of a recirculating repeater with the following "moderate quality" requirements:

output SNR = 25 dB

harmonic distortion = -25 dB (below fundamental)

The following system parameters are assumed:

detector quantum efficiency = 1 dB

fiber loss (at 1.3 μm) = 0.5 dB/km

loop loss = 1 dB

The initial modulation index m_o is chosen to be 0.5. Applying the results presented in previous sections, the maximum fiber length that can be used can be determined. The maximum total delay time is plotted in Figures 12 and 13 versus the number of passes around the loop.

[11] K. Petermann, "Gain and Index-guided Injection Lasers for Wideband Communication", Proc. 7th ECOC, Copenhagen, Sept. 1981, paper 10.1.

[12] G. Arnold, "Influence of Optical Feedback on the Noise Behavior of Injection Lasers", Proc. 7th ECOC, Copenhagen, Sept. 81, paper 10.4.
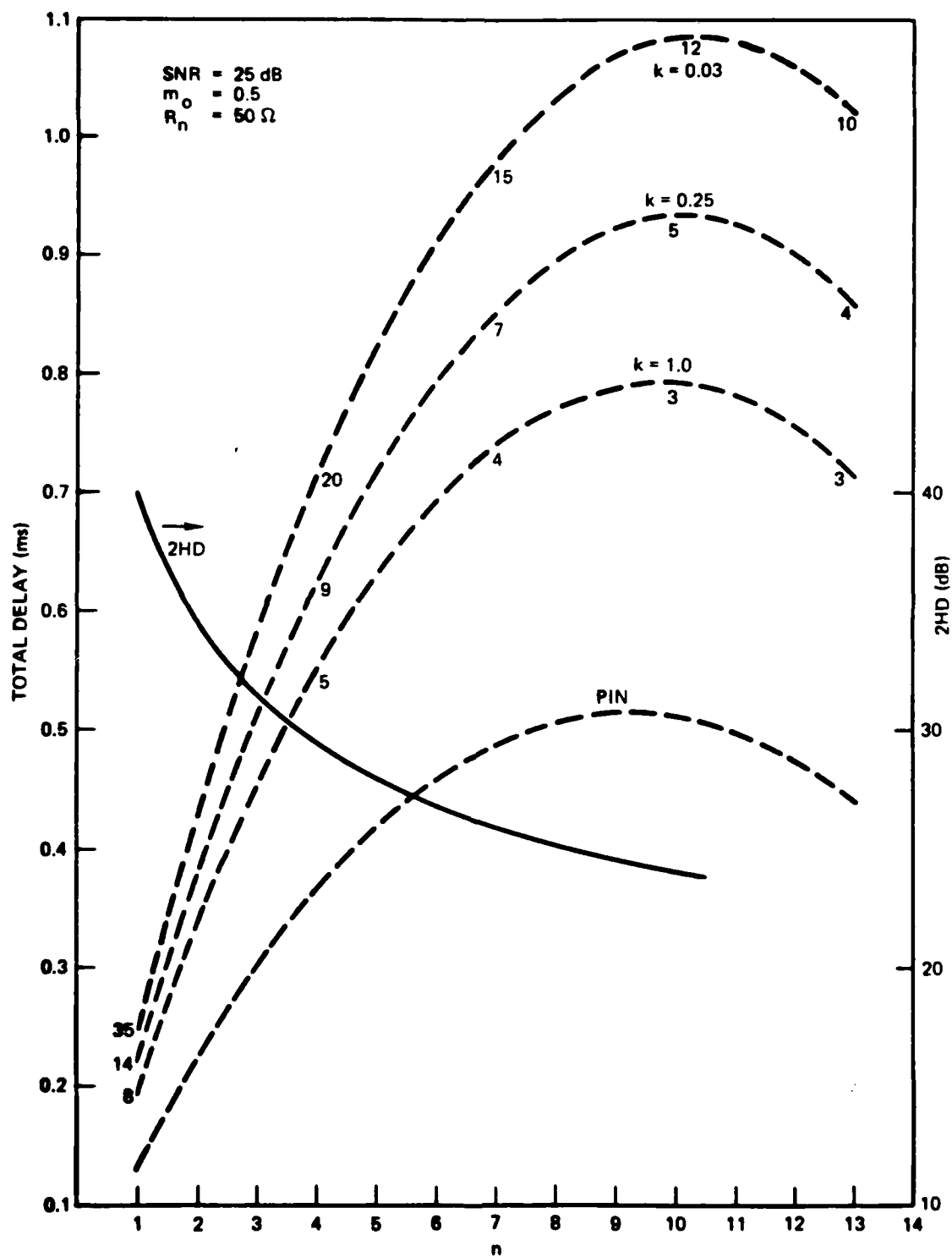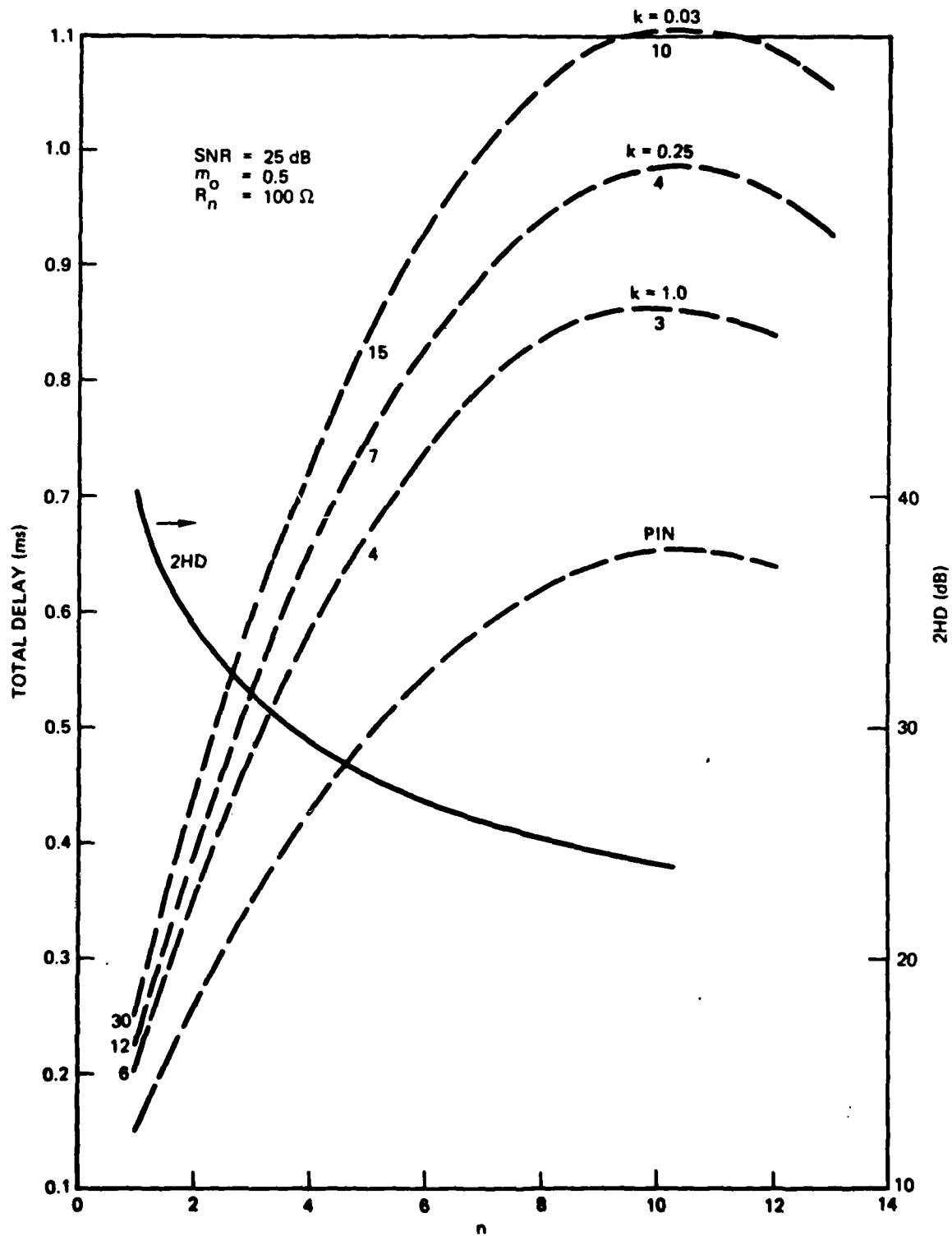
Figure 12. Total delay time for SNR = 25dB.

Figure 13. Total delay time for SNR = 25 dB.

-26-

The amplifier noise resistance in Figures 12 and 13 are 50 ohms and 100 ohms respectively. Also shown in these figures (ordinate to the right) is a curve of the second-harmonic-distortion after n passes (third harmonic distortion is negligible unless an "i.f." system which places second distortion "out of band", is being used; or if second harmonic distortion is intentionally nulled out at an inflection point). The numbers below the APD curves indicate the optimum avalanche gain required.

It can be seen that there exists an optimum value for the number of passes around the loop at which a maximum total delay time is achieved. For the 50 ohm amplifier, a total delay of 515 microseconds can be obtained (after 9 passes through 11.5 km of fiber) with a p-i-n photodiode. Using the best APD with k = 0.03, the total delay can be increased to 1.09 milliseconds (after 10 passes through 21.8 km of fiber). The harmonic distortion in both cases are approximately 24 dB below the fundamental. If the 100 ohm amplifier is used (Figure 13), the total delay with the p-i-n receiver is now 655 microseconds (after 10 passes through 13.1 km of fiber). For the k = 0.03 APD, the total delay is 1.11 milliseconds (after 10 passes through 22.2 km of fiber). It should be noted here that in order to preserve the system bandwidth at 1 GHz after such long fiber length, the fiber bandwidth has to be better than 250 GHz-km.

It remains to determine whether laser intrinsic noise can be neglected. With an assumed laser dc-signal-to-noise ratio of 150 dB/Hz, the peak signal-to-noise ratio with 0.5 modulation index and 1 GHz bandwidth is 54 dB. For the recirculating repeater with 10 passes considered here, the initial $(SNR)_1$ requirement is only 40.5 dB. Thus, laser intrinsic noise is indeed negligible.

4.3 HIGH QUALITY REPEATER

We now consider a recirculating repeater with higher quality requirements as follows:

output SNR = 35 dB

harmonic distortion = -35 dB (below fundamental)

In order to satisfy the distortion requirement, a smaller value of modulation index $(m_0 = 0.25)$ is required. Other system parameters are as before. The results are shown in Figure 14 (50 ohm noise resistance amplifier) and Figure 15 (100 ohm noise resistance amplifier).

It can be seen that the optimum number of passes is now only 2 or 3. The total achievable delay time is also much smaller, ranging from 58 microseconds (after 2 passes through 5.8 km of fiber) for a p-i-n diode, 50 ohm receiver to 154 microseconds (after 3 passes through 10.3 km of fiber) for a $k = 0.03$ APD, 100 ohm receiver. The harmonic distortion in both cases are 40 dB and 37 dB below fundamental respectively. It should be noted that the total delay time can be longer if the coupled laser power increases. For example, if 0 dBm optical power is coupled into the fiber, the total delay time with a $k = 0.03$ APD, 100 ohm receiver is increased to 258 microseconds (after 4 passes through 13 km of fiber).

The initial $(SNR)_1$ required in this case is 41 dB (for $n = 3$). The signal-to-noise ratio due to intrinsic laser noise for a modulation index of 0.25 is 49 dB. Thus it can be seen that the intrinsic laser noise can also be neglected for this case. The total delay time plotted in Figures 12 to 15 scales directly with fiber loss. Thus, if a higher loss fiber is used, the delay time will decrease proportionately.
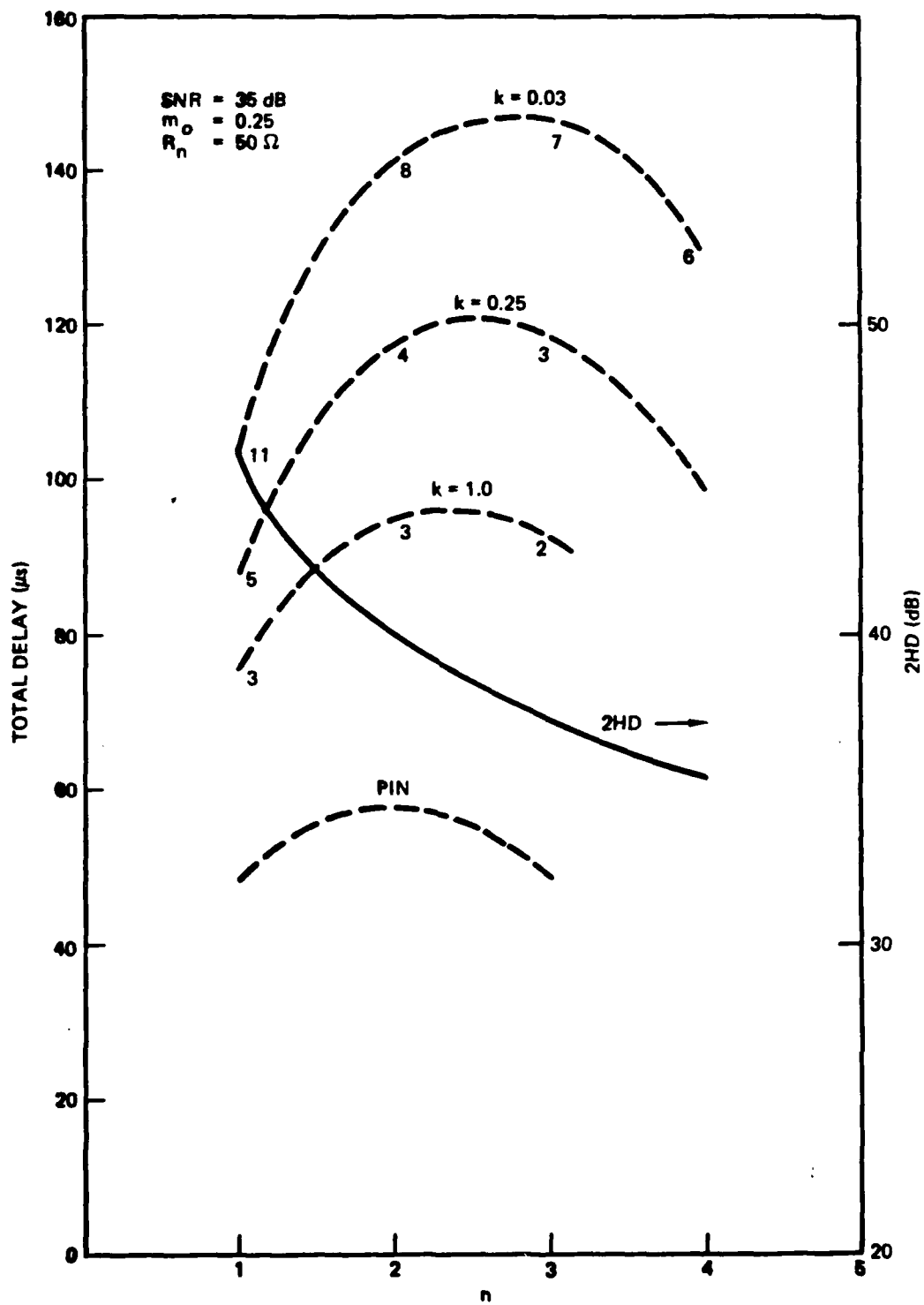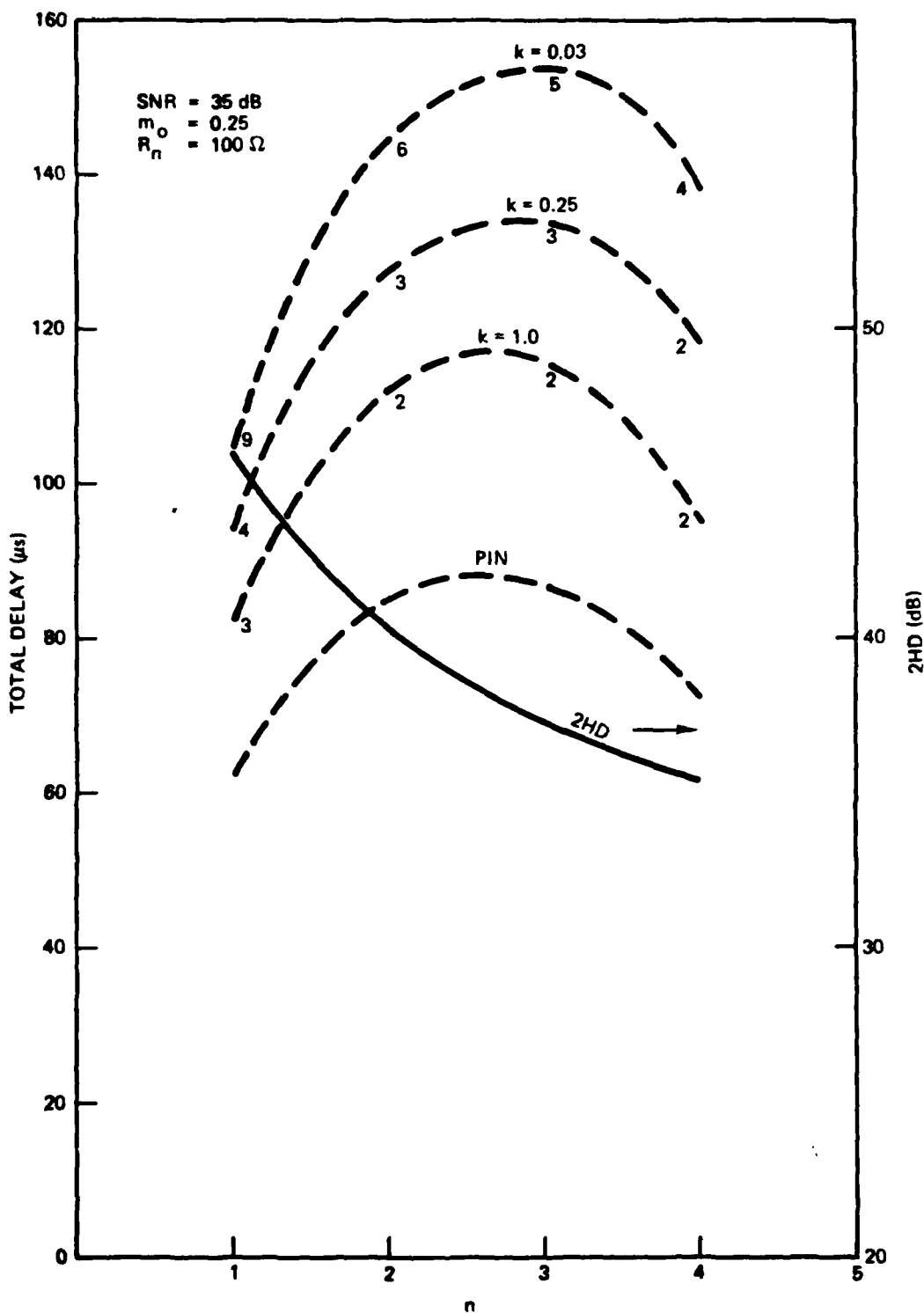
Figure 14. Total delay time for SNR = 35 dB.

Figure 15. Total delay time for SNR = 35 dB.

5.0 NOISE & DISTORTION DUE TO LASER-FIBER INTERACTION

We now consider extra sources of noise and distortion that occur
when the laser is coupled to the optical fiber. For single-mode fiber
systems, the optical source should ideally be coherent and oscillate at
a single frequency. Practical laser diodes, however, are far from
ideal. Single-longitudinal mode oscillation can be achieved by using
index-guided lasers (e.g. buried heterostructure BH, channel-substrate-
planar CSP, traverse junction stripe TJS lasers...) biased well above
threshold [13,14]. However, under modulation with temperature variation
and aging, either wavelength shift and/or mode jumping between adjacent
longitudinal modes can result. This source wavelength variation
interacts with wavelength-dependent loss and dispersion in the optical
fiber to create excess noise and harmonic distortion at the fiber output.

5.1 POLARIZATION MODAL DISTORTION AND NOISE [15]

Single mode fibers actually support two orthogonally polarized
modes which propagate at slightly different velocities due to bire-
fringent effects in the fibers (caused by fiber core ellipticity,
bends, internal stresses...). Thus, the state of polarization
within the fiber line becomes wavelength-dependent and changes
significantly with only small changes in the source wavelength.

[13] M. Nakamura et al, "Single Mode Semiconductor Injection Lasers
for Optical Fiber Communications", IEEE Jour. Quant. Elec. QE-17,
June 1981, pp 995-1005.

[14] G. Arnold et al, "Intrinsic Noise of Semiconductor Lasers in Optical
Communication Systems", Opt. Quan. Elec., 12, 1980, pp 207-219.

[15] R.E. Epworth et al, "Polarization Modal Noise and Fiber Birefringence
in Single Mode Fiber Systems", Proc. 3rd IOOC, April 1981, p. TUF2.

If there is a source of polarization selective loss (e.g. bends, misaligned fiber joints...), source wavelength variations will be converted to optical power variations resulting in noise and distortion.

Where a laser diode is directly modulated, not only the optical power is being modulated but the emission wavelength is also modulated as well [16,17] (this effect is often referred to as "chirping".) The resulting frequency deviation is of the order of 1 GHz for typical single longitudinal mode index-guided lasers. Polarization modal distortion due to this wavelength modulation has been estimated [18ab]. For a modulation frequency of 500 MHz and typical single-mode lasers, if the second harmonic distortion is not to exceed -40 dB, the polarization delay difference in the fiber length has to be less than 40 ps. This requirement puts a limit on the maximum fiber length that can be used. Typical single mode fibers operating at 1.3 μm have residual stress birefringence with a beat length of the order of 1 m, corresponding to a polarization delay difference of about 4.3 ps/km [19]. Thus, in order to satisfy the -40 dB second harmonic distortion, the total fiber length cannot be greater than 10 km. Special low birefringent fibers can be used to extend the allowable fiber length (e.g. with a polarization beat length greater than 10 m, the fiber length can be more than 100 km). Another alternative is using polarization maintaining single mode fibers.

[16] M. Nakamura et al, "Longitudinal Mode Behaviors of Mode-Stabilized AlGaAs Injection Easers", J. Appl. Phys., 49, Sept. 1978, pp 4644-4648.

[17] R.E. Epworth, "The Measurement of Static and Dynamic Coherence Phenomena Using a Michelson Interferometer," proc 5th ECOC, Sept. 1979, p. 4.2.

[18a] K. Petermann, "Non-Linear Transmission Behavior of a Single Mode Fiber Transmission Line Due to Polarization Coupling," Jour. Opt. Comm, 2, 1981, pp 59-64.

[18b] K. Pertermann, "Transmission Characteristics of a Single Mode Fiber Transmission Line With Polarization Coupling", Proc. 7th ECOC, Copenhagen, Sept. 81, paper 3.2.

[19] D. Marcuse, "Low Dispersion Single Mode Fiber Transmission - the Questions of Practical versus Theoretical Maximum Transmission Bandwidth", IEEE Jour. Quan. Elec., QE-17, June 1981, pp 869-878.

However, it is often the case in single mode fiber systems that the larger source emission frequency change due to mode jumping tends to dominate the source wavelength modulation effects described above [20] (a jump between two adjacent longitudinal modes $1A^O$ apart corresponds to a frequency shift of approximately 20 GHz). Thus, a stricter requirement than that estimated above may be necessary.

Polarization modal noise arises when the source wavelength variation is not related to the modulating signal but instead is random. Typical single longitudinal mode lasers have FM noise deviations of the order of 10 to 100 MHz when unmodulated [20]. This deviation may be modified by the applied modulation and dominated by the random mode jumping between adjacent longitudinal modes. The magnitude of this modal noise has not been analyzed quantitatively and thus has to be measured for the particular system under consideration.

5.2 MODAL PARTITION NOISE

Modal partition noise arises because of the random fluctuation in the partition of laser power among different modes. The noise portions of different lasing modes tend to cancel one another, resulting in a total laser noise which is much smaller than the noise of each individual mode. However, in transmission through a fiber, different laser modes have different delays because of chromatic dispersion. Thus at the fiber output, the noise portions of different laser modes no longer compensate one another, resulting in modal partition noise.

Modal partition noise is relatively low for a single-longitudinal mode laser but does occur because a portion of the laser power is carried by the non-lasing modes. However, modal partition noise becomes very severe if the laser is in the unstable state of jumping between two adjacent longitudinal modes.

[20] R.E. Epworth, "Modal Noise - Causes and Cures", Laser Focus, Sept. 81, pp 109-115.

At the 1.3 μm wavelength of minimum chromatic dispersion, modal partition noise is greatly reduced. The magnitude of modal partition noise can be estimated as a function of fiber chromatic dispersions [14]. An increase in the laser noise of 10 to 20 dB due to modal partition noise can be expected for a total chromatic dispersion of 60 ps [14,18ab]. If a typical single mode fiber with 3 ps/nm/km dispersion and a single mode laser with 1 nm spectral width are used, this would correspond to a total fiber length of about 20 km.

In order to appreciate the effect of modal partition noise, the intrinsic quantum noise of the laser has to be considered. The dc signal-to-noise ratio of good index-guided lasers have been measured at about 150 dB/Hz [11,12]. With a signal bandwidth of 1 GHz and a modulation index of m = 0.5, the peak-signal-to-noise ratio that can be expected is 54 dB. Thus it can be seen that modal partition noise can bring the limit of signal-to-noise ratio (due to laser noise) down to 40 dB. Also, it should be remembered that the above limit on signal-to-noise ratio decreases with smaller modulation index.

5.3 NOISE AND DISTORTION DUE TO REFLECTED OPTICAL POWER

Optical power can be coupled back into the laser cavity due to reflections in the transmission paths. Two types of reflections need to be considered since they have different effects on the laser characteristics [11,21,22]. Near-end reflection occurs when the reflection point is close (less than several cm) to the laser (e.g. due to laser-fiber coupling lens, fiber endface) while far-end reflections are reflections at longer distances (e.g. from fiber connectors and splices even at several km away).

[21] Y.C. Chen, "Noise Characteristics of Semiconductor Laser Diodes Coupled to Short Optical Fibers", Appl. Phys. Lett., 37, Oct 1980, pp 587-589.

[22] T. Kamada & K. Nawata, "Injection Laser Characteristics Due to Reflected Optical Power", IEEE J. Quant. Elec. QE-15, July 1979, pp 559-565.

Near end reflections cause fluctuation in the laser wavelength
and optical power [22,23,24]. The laser oscillation is under the
influence of two cavities: the internal laser cavity (between the
two laser mirrors) and an external cavity formed by the laser
mirror and the reflection surface. The laser oscillates at the single
longitudinal mode closest to the gain peak which coincides with one
of the external cavity modes. If there is a shift in resonance
frequencies of either or both cavities (e.g. due to temperature
effects), the interference between the two modes becomes less
constructive, resulting in a reduction of optical power output.
As the mismatching increases, the laser will switch its oscillating
frequency to another longitudinal mode where a better match
between the two cavity modes is obtained.

Problems due to near-end reflections can be avoided by proper
design of the laser-fiber coupling configuration to keep the
coupling elements rigid [22,25].

Far-end reflections produce periodic sharp peaks in the frequency
response of the laser [12]. The laser noise also increases sharply
at these periodic frequencies which are determined by the reciprocal
of the round trip time of the light in the external cavity [21,22,
26,27]. If the reflection is caused by a connector a distance d

[23] R. Lange & K. Kobayashi, "External Optical Feedback Effects on
     Semiconductor Injection Laser Properties", IEEE Jour. Quant. Elect.,
     QE-16, March 1980, pp 347-355.

[24] O. Hirota & Y. Suematsu, "Noise Properties of Injection Lasers due
     to Reflected Waves", IEEE Jour. Quan. Elec., QE-15, March 1979, pp 142-149.

[25] M. Saruwatari & T. Sugie, "Efficient Laser Diode to Single Mode
     Fiber Coupling Using a Combination of Two Lenses in Confocal Condition",
     IEEE Jour. Quan. Elec., QE-17, June 1981, pp 1021-1027.

[26] J. Ikushima & M. Maeda, "Self-Coupled Phenomena of Semiconductor
     Lasers Caused by an Optical Fiber", IEEE Jour. Quan. Elec, QE-14,
     May 1978, pp 331-332.

[27] O. Hirota et al, "Properties of Intensity Noises of Laser Diodes Due
     to Reflected Waves from Single Mode Optical Fibers and Its Reduction",
     IEEE Jour. Quant. Elec., QE-17, June 1981, pp 1014-1020.

away from the laser, these sharp peaks will occur at multiple of
$c/2nd$ where c is the velocity of light and n is the fiber refractive
index. In addition to this excess distortion and noise, the laser
spectrum can also be severely effected. Mode jumping, satellite
mode generation and spectral line broadening have been observed
[22,28]. This spectral instability creates further distortion and
noise by the effects described in previous sections. It has also
been reported that the excess noise due to optical power feedback
is enhanced by direct modulation of the laser [27].

The excess noise level is dependent on the amount of light
coupled back into the laser. Thus, a reflection a long distance
away from the laser is less severe than the same reflection closer
to the laser. The exact excess noise has to be measured for the system
under consideration. Degradation of the laser dc-signal-to-noise
ratio of 10 dB due to reflected light has been measured for index-guided
lasers [12]. It is noted here that as far as problems due to reflected
optical power are concerned, the gain-guided lasers are much more
tolerable because of their short coherent lengths and multimodal
spectra.

To minimize problems due to reflected light, one has to take
care to minimize any reflection in the system as much as possible
(e.g. by index matching fluid). In particular, optical connectors
within the coherence length of the laser (e.g. a connector between
the laser fiber pigtail and the transmission fiber) have to be avoided
if possible (replaced by fusion splices). Complete elimination of
reflected power problems is also possible by using an optical isolator.
However, the insertion loss reported for 1.3 μm single mode optical
isolators is still relatively high (6dB [29]).

[28] A Dandridge & R. Miles, "Spectral Characteristics of Semiconductor
Laser Diodes Coupled to Optical Fibers", Elec. Lett., 17, No. 7, 2nd
April 1981, pp 273-274.

[29] K. Kobayashi et al, "Micro-optic Grating Multiplexers and Optical
Isolators for Fiber Optic Communications", IEEE J. Quant. Elec.,
QE-16, Jan 1980, pp 11-22.

6.0 CONCLUSIONS

In this report, we have investigated in detail the theoretical performance of a 1 GHz bandwidth recirculating optical analog repeater. Both p-i-n photodiodes and several types of 1.3 μm APDs were considered in order to compare their performance. Important system parameters were identified and their effects on the maximum achievable delay time were reported. It was shown that the maximum total delay time depends strongly on the requirements on the signal quality. For a 25 dB signal-to-noise and signal-to-distortion ratio requirement, the total achievable delay is of the order of 0.5 to 1 millisecond. However, if the signal-to-noise and signal-to-distortion requirement is increased to 35 dB, the total delay time that can be achieved drops by an order of magnitude (50 to 150 microseconds).

Any extra noise and nonlinear distortion that can occur due to fiber-laser interactions will further reduce the total achievable delay time. These subtle distortion and noise sources have been discussed in detail. It has been seen that spectral stability of the laser is important in minimizing polarization and modal partition noise and distortion. Thus it may be necessary to keep the laser temperature well-stabilized or use some form of longitudinal mode control. Reflections in the transmission path should also be minimized in order to avoid feedback problems.

REFERENCES

1. J.L. Hullett & T.V. Muoi, "A Feedback Receiver Amplifier for Optical Transmission Systems", IEEE Trans. Comm., COM-24, Oct. 1976 pp 1180-1185.

2. R.G. Smith & S.D. Personick, "Receiver Design for Optical Fiber Communication Systems", Chp. 4 in Semiconductor Devices for Optical Communication, Springer-Verlag, 1980.

3. J.E. Goell, "Input Amplifiers for Optical PCM Recivers", BSTJ, Vol 53, Nov. 1974, pp 1771-1793.

4. R.J. McIntyre, "Multiplication Noise in Uniform Avalanche Junctions", IEEE Trans. Elec. Dev., ED-13, Jan. 1966, pp 164-168.

5. T.P. Pearsall, "Photodetectors for Optical Communication", Jour. Opt. Comm., Vol 2, June 1981, pp. 42-48.

6. J. Meslage et al., "Fast, High Gain 1.3 μm HgCdTe Photodiode", Proc. 7th ECOC, Copenhagen, Sept. 1981, paper 11.4.

7. K. Stubkjaer et al, "Nonlinearities of GaAlAs Lasers - Harmonic Distortion", IEEE Jour. Quant. Elec., QE-16, May 1980, pp 531-537.

8. M. Maeda et al, "Harmonic Distortions in Semiconductor Injection Lasers", Proceed. 5th ECOC, Sept. 1979, Paper 18.5.

9. K. Nagano et al, "Optimizing Optical Transmitters and Receivers for Transmitting Multichannel Video Signals Using Laser Diodes", IEEE Trans. Comm., COM-29, Jan. 1981, pp 41-45.

10. G. Grobkopf et al, "Measurement of Non-linear Distortion in Index- and Gain-Guiding GaAlAs Lasers", Jour. Opt. Comm., Vol. 1, Sept. 1980, pp 15-17.

11. K. Petermann, "Gain and Index-Guided Injection Lasers for Wideband Communication", Proc. 7th ECOC, Copenhagen, Sept. 1981, paper 10.1.

12. G. Arnold, "Influence of Optical Feedback on the Noise Behavior of Injection Lasers", Proc. 7th ECOC, Copenhagen, Sept. 81, paper 10.4.

13. M. Nakamura et al, "Single Mode Semiconductor Injection Lasers for Optical Fiber Communications", IEEE Jour. Quant. Elec. QE-17, June 1981, pp 995-1005.

14. G. Arnold et al, "Intrinsic Noise of Semiconductor Lasers in Optical Communication Systems", Opt. Quan. Elec., 12, 1980, pp 207-219.

15. R.E. Epworth et al, "Polarization Modal Noise and Fiber Birefringence in Single Mode Fiber Systems", Proc. 3rd IOOC, April 1981, p. TUF2.

16. M. Nakamura et al, "Longitudinal Mode Behaviors of Mode-Stabilized AlGaAs Injection Easers", J. Appl. Phys., 49, Sept. 1978, pp 4644-4648.

17. R.E. Epworth, "The Measurement of Static and Dynamic Coherence Phenomena Using a Michelson Interferometer," proc 5th ECOC, Sept. 1979, p 4.2.

18a. K. Petermann, "Non-Linear Transmission Behavior of a Single Mode Fiber Transmission Line Due to Polarization Coupling," Jour. Opt. Comm., 2, 1981, pp 59-64.

18b. K. Petermann, "Transmission Characteristics of a Single Mode Fiber Transmission Line With Polarization Coupling", Proc. 7th ECOC, Copenhagen, Sept. 81, paper 3.2.

19. D. Marcuse, "Low Dispersion Single Mode Fiber Transmission - The Question of Practical Versus Theoretical Maximum Transmission Bandwidth", IEEE Jour. Quan. Elec., QE-17, June 1981, pp 869-878.

20. R.E. Epworth, "Modal Noise - Causes and Cures", Laser Focus, Sept. 81, pp 109-115.

21. Y.C. Chen, "Noise Characteristics of Semiconductor Laser Diodes Coupled to Short Optical Fibers", Appl. Phys. Lett., 37, Oct 1980, pp 587-589.

22. T. Kamada & K. Nawata, "Injection Laser Characteristics Due to Reflected Optical Power", IEEE J. Quant. Elec. QE-15, July 1979, pp 559-565.

23. R. Lang & K. Kobayashi, "External Optical Feedback Effects on Semiconductor Injection Laser Properties", IEEE Jour. Quant. Elect., QE-16, March 1980, pp 347-355.

24. O. Hirota & Y. Suematsu, "Noise Properties of Injection Lasers due to Reflected Waves", IEEE Jour. Quan. Elec., QE-15, March 1979, pp 142-149.

25. M. Saruwatari & T. Sugie, "Efficient Laser Diode to Single Mode Fiber Coupling Using a Combination of Two Lenses in Confocal Condition", IEEE Jour. Quan. Elec., QE-17, June 1981, pp 1021-1027.

26. J. Ikushima & M. Maeda, "Self-Coupled Phenomena of Semiconductor Lasers Caused by an Optical Fiber", IEEE Jour. Quan. Elec, QE-14, May 1978, pp 331-332.

27. O. Hirota et al., "Properties of Intensity Noises of Laser Diodes Due to Reflected Waves from Single Mode Optical Fibers and Its Reduction", IEEE Jour. Quant. Elec., QE-17, June 1981, pp 1014-1020.

28. A. Dandridge & R. Miles, "Spectral Characteristics of Semiconductor Laser Diodes Coupled to Optical Fibers", Elec. Lett., 17, No. 7, 2nd April 1981, pp 273-274.

29. K. Kobayashi et al, "Micro-optic Grating Multiplexers and Optical Isolators for Fiber Optic Communications", IEEE, Jour. Quant. Elec., QE-16, Jan 1980, pp 11-22.

MED

8