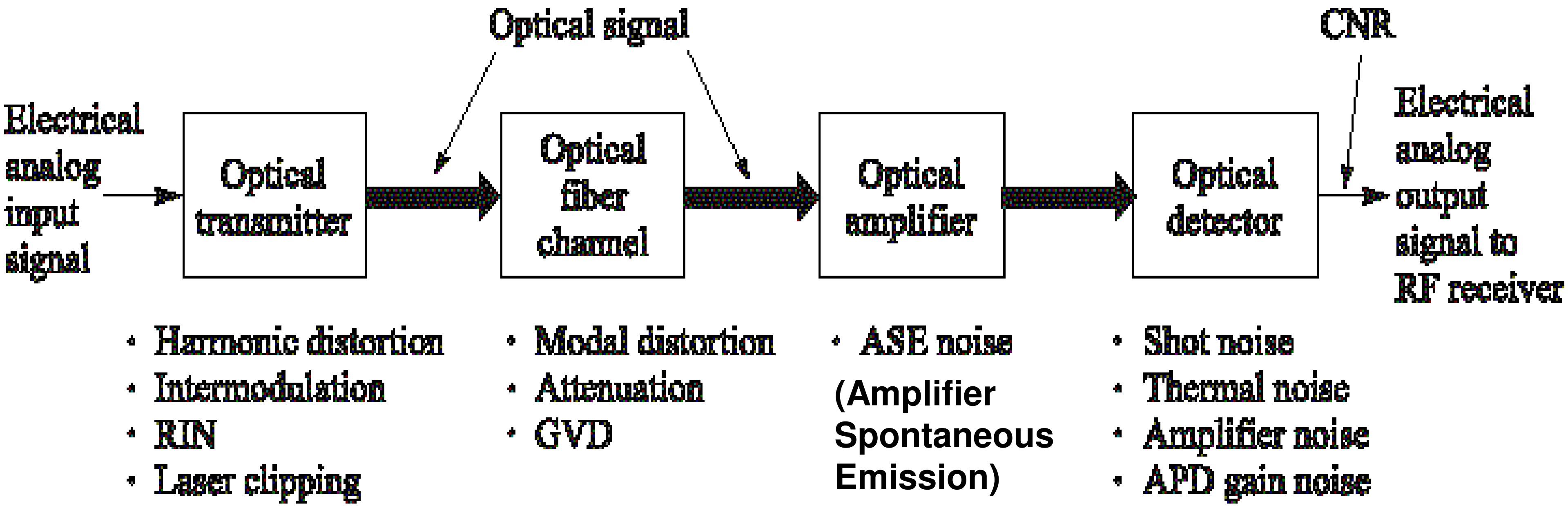
Chapter 9

Analog Links

Content

- **Overview of Analog Links**
- **Carrier-to-Noise Ratio (CNR)**
  - **Carrier Power**
  - **Photo-detector and Pre-amplifier Noises**
  - **Relative Intensity Noise (RIN)**
  - **Reflection Effects on RIN**
  - **Limiting Conditions on CNR**
- **Multichannel Fiber Transmissions**
  - **Multichannel Amplitude Modulation**
  - **Multichannel Frequency Modulation**
  - **Subcarrier Multiplexing**

Analog Communication Links



Analog (RF) links are used where converting to digital signals is undesirable, including

- Analog TV and audio services
- Cable modem services
- Microwave-multiplexed signals (e.g., satellite base stations)
- Radar signal processing

Overview of Analog Links

- A bias point on the source is set approximately at the midpoint of the linear output region. The analog signal can then be sent with direct intensity modulation technique.
- Other modulation techniques include AM, FM and PM, which first convert baseband signal onto an electrical subcarrier prior to intensity modulation.
- Signal impairments in optical source : harmonic distortions, inter-modulation (IM) products, RIN in the laser, and laser clipping.
- The fiber should have a flat amplitude and group-delay response within the passband required to send the signal free of linear distortion.
- Since modal-distortion-limited bandwidth is difficult to equalize, it is best to choose a single-mode fiber.

Carrier-to-Noise Ratio

- The ratio of rms carrier power to rms noise power at the input of the RF receiver is known as the *carrier-to-noise ratio* (CNR).
- For the FSK modulation scheme, BERs of 10^{-9} and 10^{-15} translate into CNR values of 36 (15.6 dB) and 64 (18.0 dB), respectively.
- Using AM for studio-quality TV signal requires a CNR of 56 dB, since the need for bandwidth efficiency leads to a high SNR. FM only needs CNR values of 15-18 dB.

Carrier-to-Noise Ratio

- If CNR_i represents the carrier-to-noise ratio related to a particular signal contaminant, then for N signal-impairment factors the total CNR is given by

$$\frac{1}{\text{CNR}} = \sum_{i=1}^{N} \frac{1}{\text{CNR}_i}$$

- For single information channel, the important signal impairments include laser intensity noise fluctuations, laser clipping, photo-detector noise, and optical-amplifier noise.

- For multiple message channels, the harmonic and inter-modulation distortions arise.

- The three dominant factors that cause signal impairments in a fiber link are shot noise, optical-amplifier noise, and laser clipping.

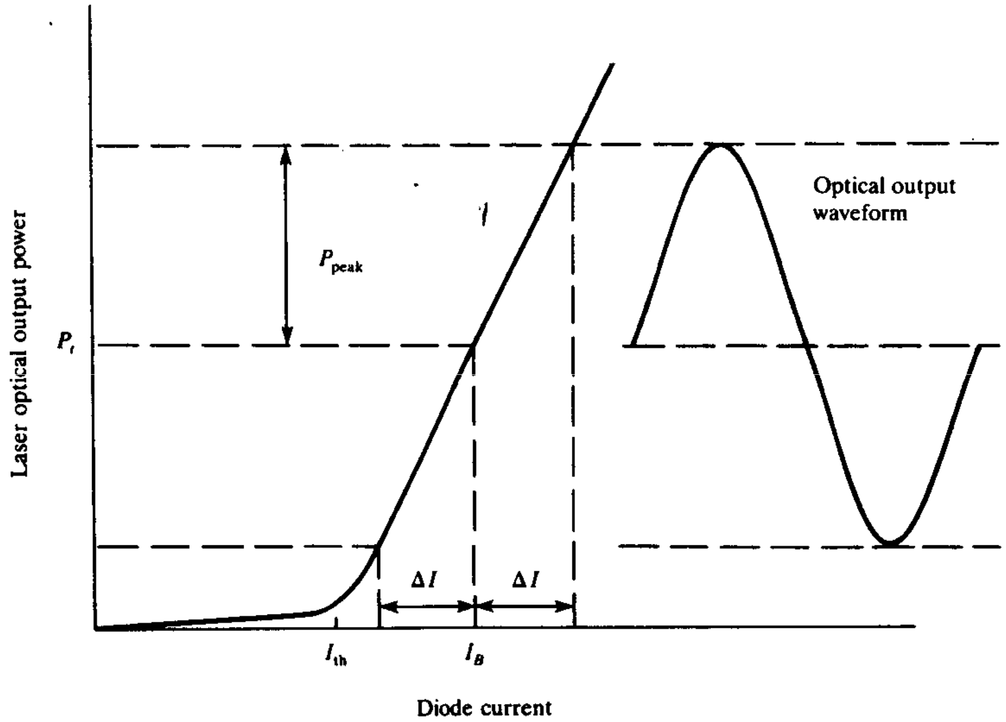
Carrier Power

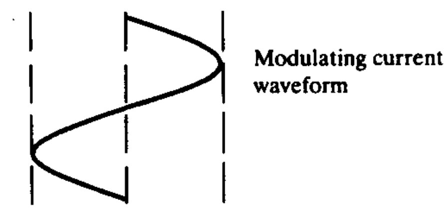
- if the time-varying analog drive signal is $s(t)$, then the envelope of the output optical power $P(t)$ has the form

$$P(t) = P_t\left[1 + ms(t)\right]$$

where P_t is the optical output power at the bias current level.

- The modulation index m is given by $m = P_{\text{peak}} / P_t$, where P_{peak} and P_t are defined in the right figure. Typical values of m for analog applications range from 0.25 to 0.50.





- For a sinusoidal received signal, C at the output of receiver is

$$C = \frac{1}{2}\left(m\mathcal{R}M\overline{P}\right)^2 \ [\mathrm{A}^2]$$

$\mathcal{R}$: Responsivity, M : gain, $\overline{P}$: average power

Photodetector and Preamplifier Noises

- For the photodiode noise,

$$\left\langle i_N^2 \right\rangle = \sigma_N^2 \approx 2q(I_p + I_D)M^2 F(M) B_e ; I_p = \mathcal{R}\overline{P}$$

- Here, I_D is the detector bulk dark current, M is the photodiode gain with $F(M)$ being its associated noise figure, and B_e is the receiver bandwidth.

- The CNR for the photodetector only is $\mathrm{CNR}_{\det} = \dfrac{C}{\sigma_N^2}$
- For the preamplifier noise,

$$\left\langle i_T^2 \right\rangle = \sigma_T^2 = \frac{4k_B T}{R_{eq}} B_e F_t$$

where R_{eq} is the equivalent resistance of the photodetector load and the preamplifier, and F_t is the noise factor of the preamplifier.
- Then, the CNR for the preamplifier only is

$$\mathrm{CNR}_{preamp} = \frac{C}{\sigma_T^2}$$

Relative Intensity Noise (RIN)

- The noise resulting from the random intensity fluctuations (due to temperature variations or spontaneous emission) is called *relative intensity noise* (RIN), which may be defined in terms of the mean-square intensity variations.
- The resultant mean-square noise current is given by

$$\left\langle i_{RIN}^2 \right\rangle = \sigma_{RIN}^2 = \mathrm{RIN}\left(\mathscr{R}\overline{P}\right)^2 B_e$$

where RIN is defined by the noise-to-signal power ratio:

$$\mathrm{RIN} = \frac{\left\langle (\Delta P_L)^2 \right\rangle}{\overline{P_L^2}} \; [\mathrm{dB/Hz}]$$

Here, $<(\Delta P_L)^2>$: mean-square intensity fluctuation, $\overline{P_L}$: average light intensity

- Then, the total CNR is given by

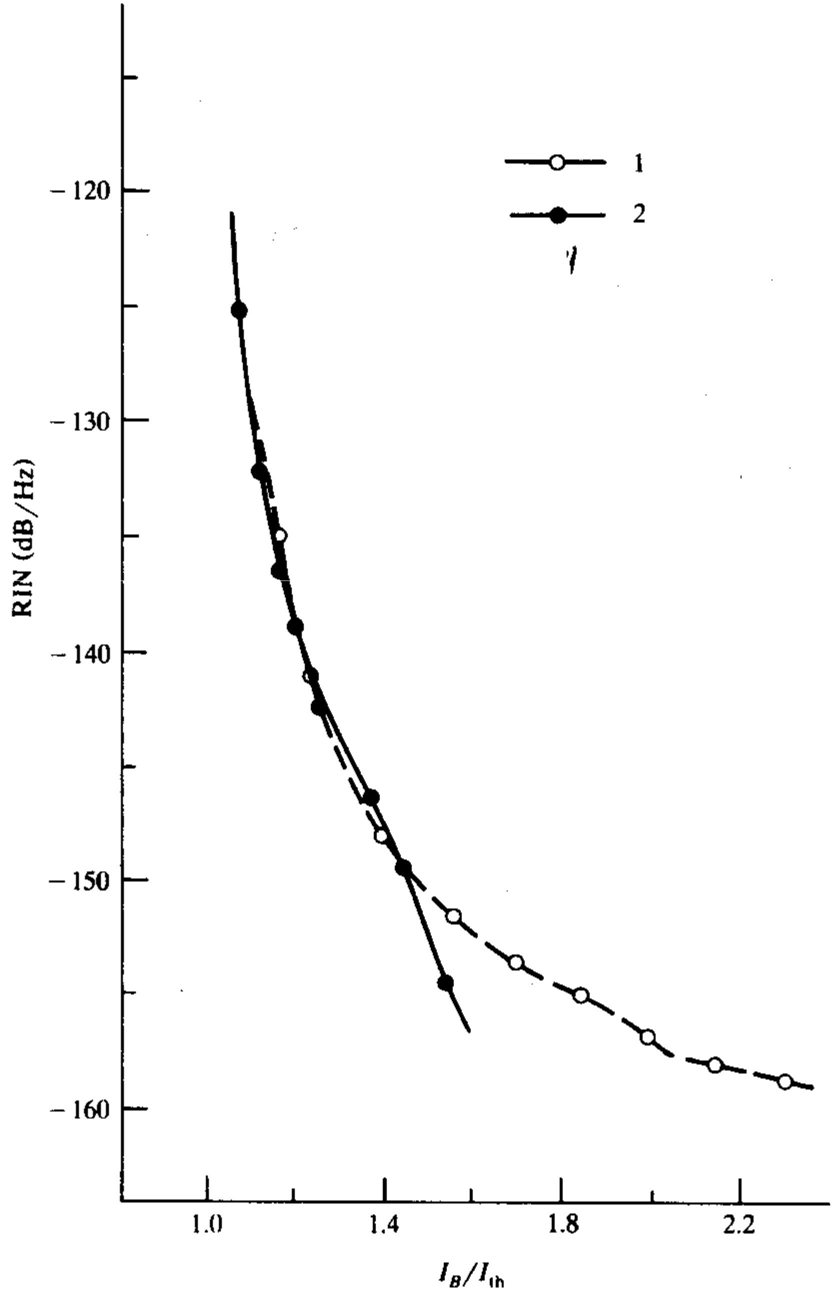
$$\mathrm{CNR} = \frac{\left(m\mathscr{R}M\overline{P}\right)^2/2}{\mathrm{RIN}\left(\mathscr{R}\overline{P}\right)^2 B_e + 2q(I_p + I_D)M^2F(M)B_e + (4k_BT/R_{eq})B_eF}$$

Relative Intensity Noise (RIN) (2)

<u>Example 9-1</u>:

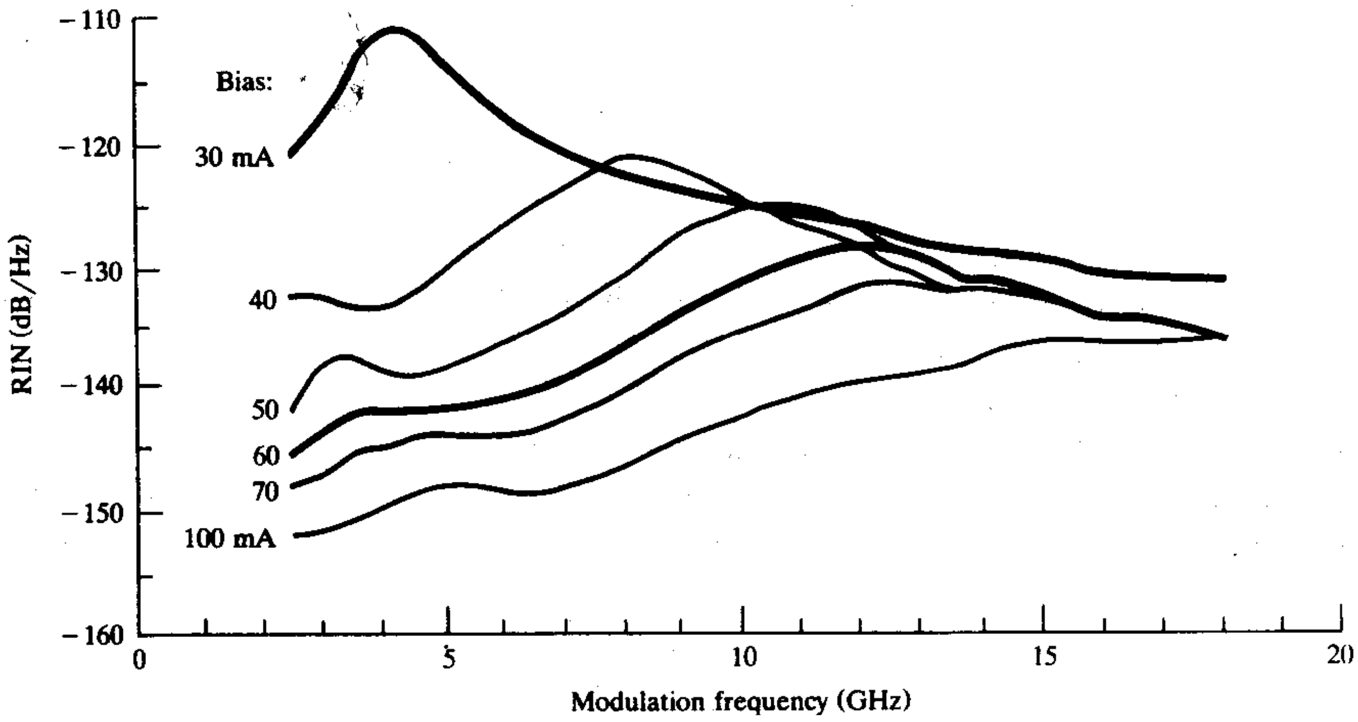
- The right figure shows RIN for two buried-heterostructure lasers. The noise level was measured at 100 MHz.

- For injection currents sufficiently above threshold (i.e., for $I_B/I_{th} > 1.2$), the RIN of these index-guided lasers lies between -140 and -150 dB/Hz.



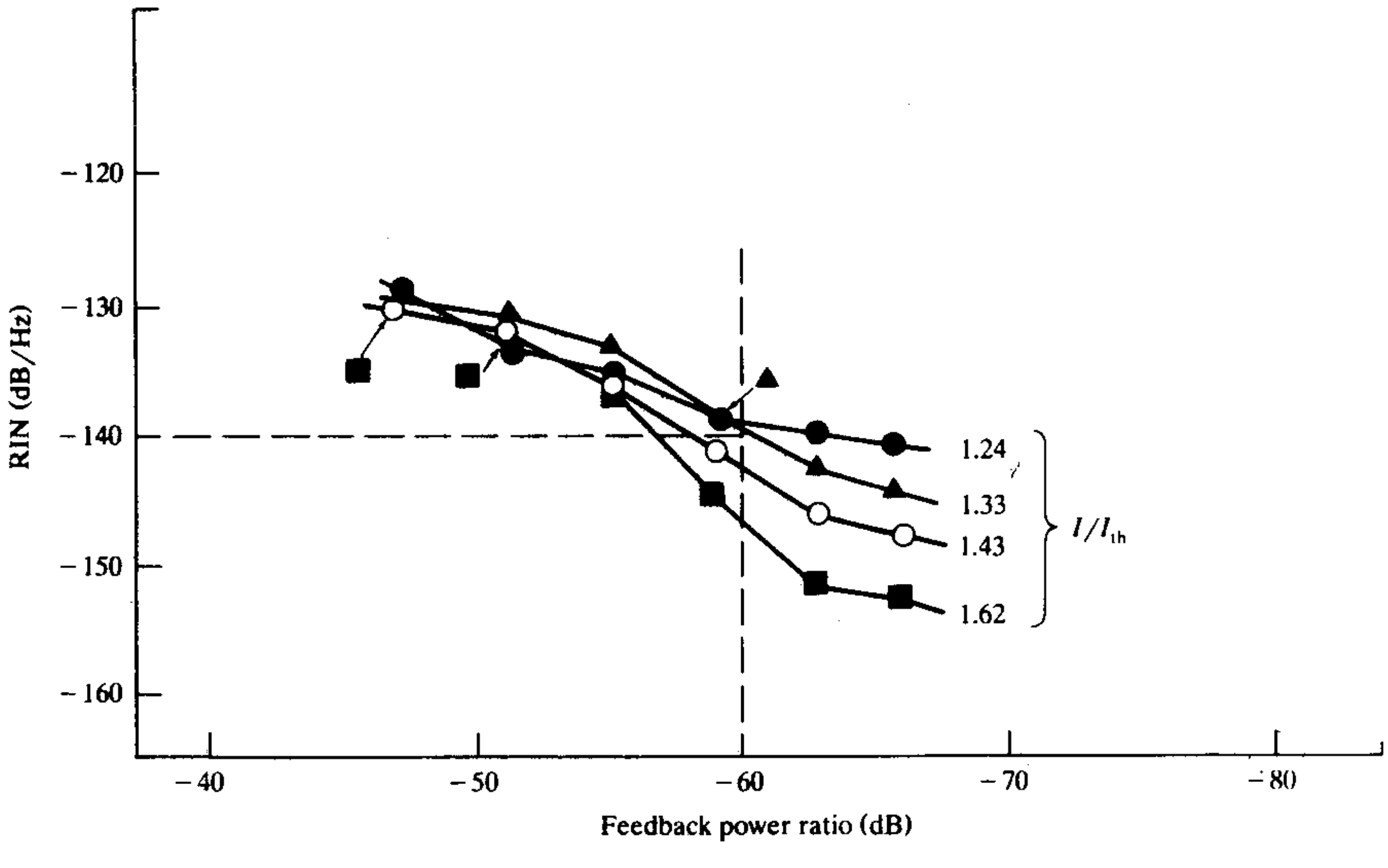
Relative Intensity Noise (RIN) (3)

<u>Example 9-2</u>: The figure below shows the RIN of an InGaAsP buried-heterostructure laser as a function of modulation frequency at several different bias levels. The RIN is essentially independent of frequency below several hundred MHz, and it peaks at the resonant frequency. At a bias level of 60-mA, which gives a 5-mW output, the RIN is typically < -135 dB/Hz for modulation frequencies up to 8-GHz. For received optical signal levels of -13 dBm (50-μW) or less, the RIN of buried-heterostructure InGaAsP lasers lies sufficiently below the noise level of a 50-Ω amplifier with a 3-dB noise figure.



Reflection Effects on RIN

Back-reflected signals can increase the RIN by 10-20 dB as shown in the figure below. These curves show the increase in RIN for bias points ranging from 1.24 to 1.62 times the threshold-current level. The feedback power ratio here is the amount of optical power reflected back into the laser relative to the light output from the source. The dashed line shows that at $1.33I_{th}$ the feedback ratio must be less than -60 dB in order to maintain an RIN of less than -140 dB/Hz.



Limiting Conditions on CNR

The dominant terms of the noise differ depending on the power level at the receiver as follows:

- Low level : the preamplifier circuit noise
- Intermediate level : the quantum noise
- High level : the RIN

Example 9-3: Consider a link with a laser transmitter and a PIN receiver having the characteristics given below.

Transmitter	Receiver
$m = 0.25$	$\mathscr{R}_0 = 0.6$ A/W
RIN $= -143$ dB/Hz	$B = 10$ MHz
$P_c = 0$ dBm	$I_D = 10$ nA
	$R_{eq} = 750\ \Omega$
	$F_t = 3$ dB

Limiting Conditions on CNR (2)

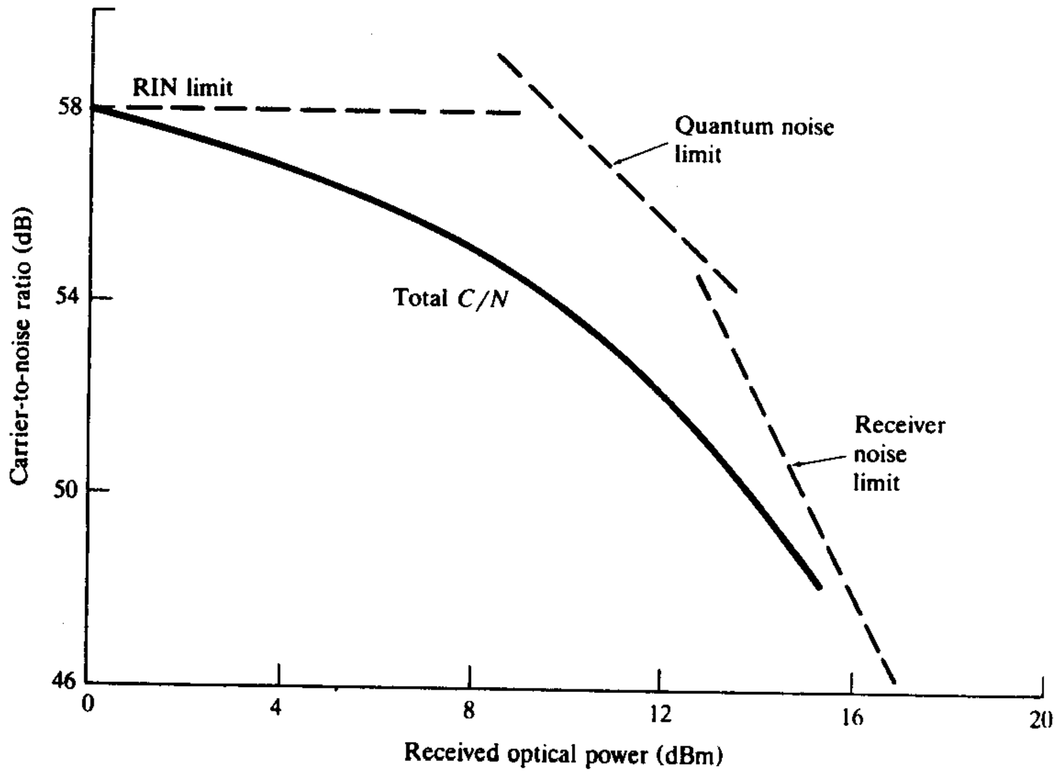
The figure below show a plot of *C/N* as a function of the optical power level at the receiver.

<u>Observations:</u>

• At high received powers the source noise dominates to give a constant *C/N*.

• At intermediate levels, the quantum noise is the main contributor, with a 1-dB drop in *C/N* for every 1-dB decrease in received optical power.

• For low light levels, the thermal noise of the receiver is the limiting noise term, yielding a 2-dB rolloff in *C/N* for each 1-dB drop in received optical power.



Multichannel Fiber Transmissions

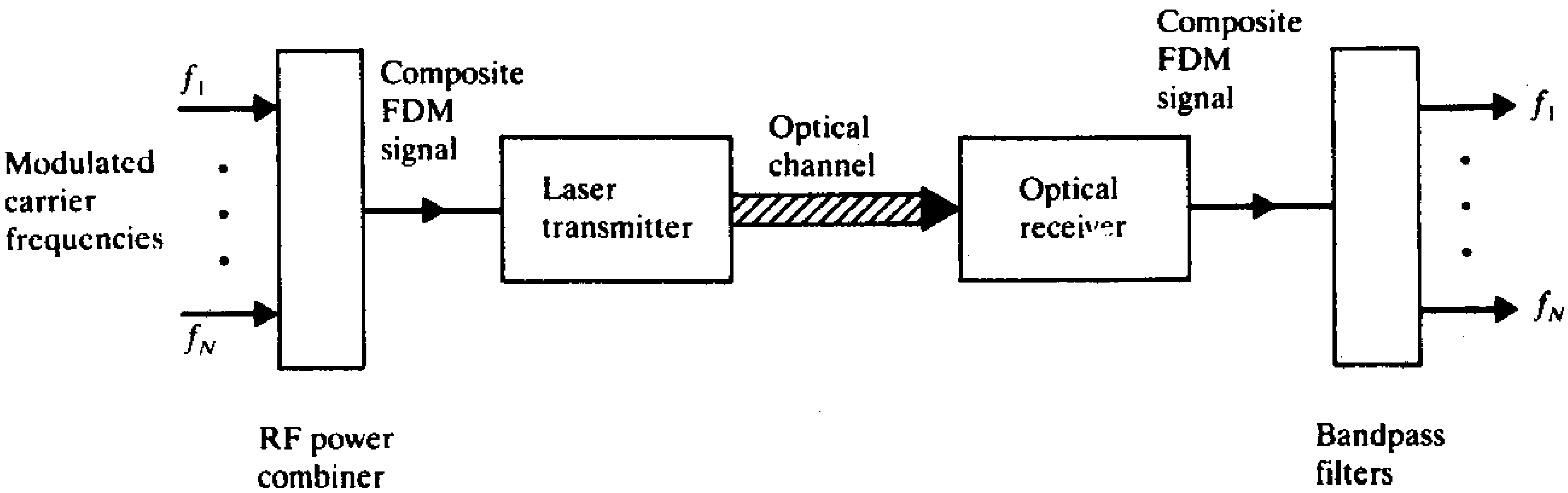
- In broadband analog applications, such as CATV super-trunks, one can employ multiplexing technique in which a number of baseband signals are superimposed on a set of N subcarriers that have different frequencies $f_1, f_2, \ldots, f_N$.
- The modulated subcarriers are combined through FDM to form a composite signal that directly modulates a single optical source.
- Methods for achieving this include VSB-AM, FM, and SCM.
- AM is simple and cost-effective in that it is compatible with the equipment interfaces of a large number of CATV customers.

Multichannel Fiber Transmissions (2)

- Although FM requires a larger bandwidth than AM, it provides a higher SNR and is less sensitive to source nonlinearities.
- Microwave SCM operates at higher frequencies than AM or FM and is an interesting approach for broadband distribution of both analog and digital signals.
- The fiber-optic-based TV networks operate in a frequency range from 50 to 88 MHz and from 120 to 550 MHz. The band from 88 to 120 MHz is reserved for FM radio broadcast.
- The CATV networks can deliver over 80 AM-VSB video channels, each having a noise bandwidth of 4 MHz within a channel bandwidth of 6 MHz, with SNRs exceeding 47 dB.

Multichannel Amplitude Modulation

- Used in CATV networks, which can deliver up to 80 AM-VSB video channels.
- The figure below depicts the technique for combining N independent messages. An *i*-th channel information-bearing signal amplitude-modulates a carrier wave that has a frequency f_i, $i = 1, 2, ..., N$.
- An RF power combiner sums these *N* amplitude-modulated carriers to yield a composite FDM signal which intensity-modulates a laser diode.
- Following the optical receiver, a bank of parallel bandpass filters separates the combined carriers back into individual channels.



Multichannel Amplitude Modulation (2)

For N channels the optical modulation index m is related to the per-channel modulation index m_i by

$$m = \left(\sum_{i=1}^{N} m_i^2 \right)^{1/2}$$

If each channel modulation index m_i has the same value m_c, then

$$m = m_c N^{1/2}$$

As a result, when N signals are frequency-multiplexed and used to modulate a single optical source, the CNR of a single channel is degraded by $10\log N$.

Multichannel Amplitude Modulation (3)

- When multiple carrier frequencies pass through a nonlinear device such as a laser diode, *inter-modulation* (IM) *products* other than the original frequencies can be produced.
- Among the IM products, only the 2^{nd}-order and 3^{rd}-order terms are considered, since higher-order products tend to be significantly smaller.
- The 3^{rd}-order IM distortion products at frequencies $f_i + f_j - f_k$ (which are known as *triple-beat IM products)* and $2f_i - f_j$ (which are known as *two-tone IM products)* are the most dominant.

Multichannel Amplitude Modulation (4)

- A 50-channel CATV network operating over 55.25-373.25 MHz has 39 second-order IM products at 54.0 MHz and 786 third-order IM tones at 229.25 MHz.

- The amplitudes of the triple-beat products are 3 dB higher than the two-tone third-order IM products.

- Since there are $N(N\text{-}1)(N\text{-}2)/2$ triple-beat terms compared with $N(N\text{-}1)$ two-tone terms, the triple-beat products tend to be the major source of IM noise.

- If a signal passband contains a large number of equally spaced carriers, several IM terms will exist at or near the same frequency. This so-called *beat stacking* is additive on a power basis.

Multichannel Amplitude Modulation (5)

- For N equally spaced equal-amplitude carriers, the number of third-order IM products that fall right on the r-th carrier is given by

$$D_{1,2} = \frac{1}{2}\left\{N - 2 - \frac{1}{2}\left[1 - (-1)^N\right](-1)^r\right\}$$

for two-tone terms of the type $2f_\mathrm{i} - f_\mathrm{j}$,

- and by

$$D_{1,1,1} = \frac{r}{2}(N - r + 1) + \frac{1}{4}\left\{(N-3)^2 - 5 - \frac{1}{2}\left[1 - (-1)^N\right](-1)^{N+r}\right\}$$

for triple-beat terms of the type $f_\mathrm{i} + f_\mathrm{j} - f_\mathrm{k}$.

Multichannel Amplitude Modulation (6)

$D_{1,2}$

N	r = 1	2	3	4	5	6	7	8
1	0							
2	0	0						
3	0	1	0					
4	1	2	2	1				
5	2	4	4	4	2			
6	4	6	7	7	6	4		
7	6	9	10	11	10	9	6	
8	9	12	14	15	15	14	12	9

$D_{1,1,1}$

N	r = 1	2	3	4	5	6	7	8
1	0							
2	0	0						
3	1	0	1					
4	1	1	1	1				
5	2	1	2	1	2			
6	2	2	2	2	2	2		
7	3	2	3	2	3	2	3	
8	3	3	3	3	3	3	3	3

Multichannel Amplitude Modulation (7)

- The results of beat stacking are commonly referred to as *composite second order* (CSO) and *composite triple beat* (CTB), and are used to describe the performance of multichannel AM links:

$$\text{CSO} = \frac{\text{peak carrier power}}{\text{peak power in composite 2}^{\text{nd}}\text{-order IM tone}}$$

$$\text{CTB} = \frac{\text{peak carrier power}}{\text{peak power in composite 3}^{\text{rd}}\text{-order IM tone}}$$

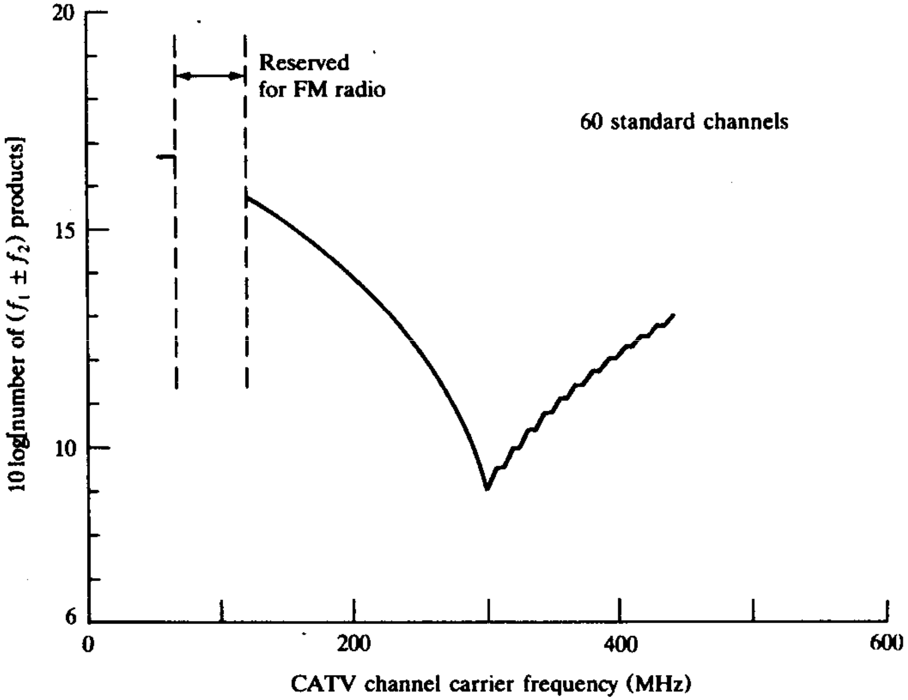
Multichannel Amplitude Modulation (8)

Example 9-4:

- Figures 9-8 and 9-9 show the predicted relative 2nd-order and 3rd-order IM performance, respectively, for 60 CATV channels in the frequency range 50-450 MHz.
- The effect of CSO is most significant at the passband edges, whereas CTB contributions are most critical at the center of the band.

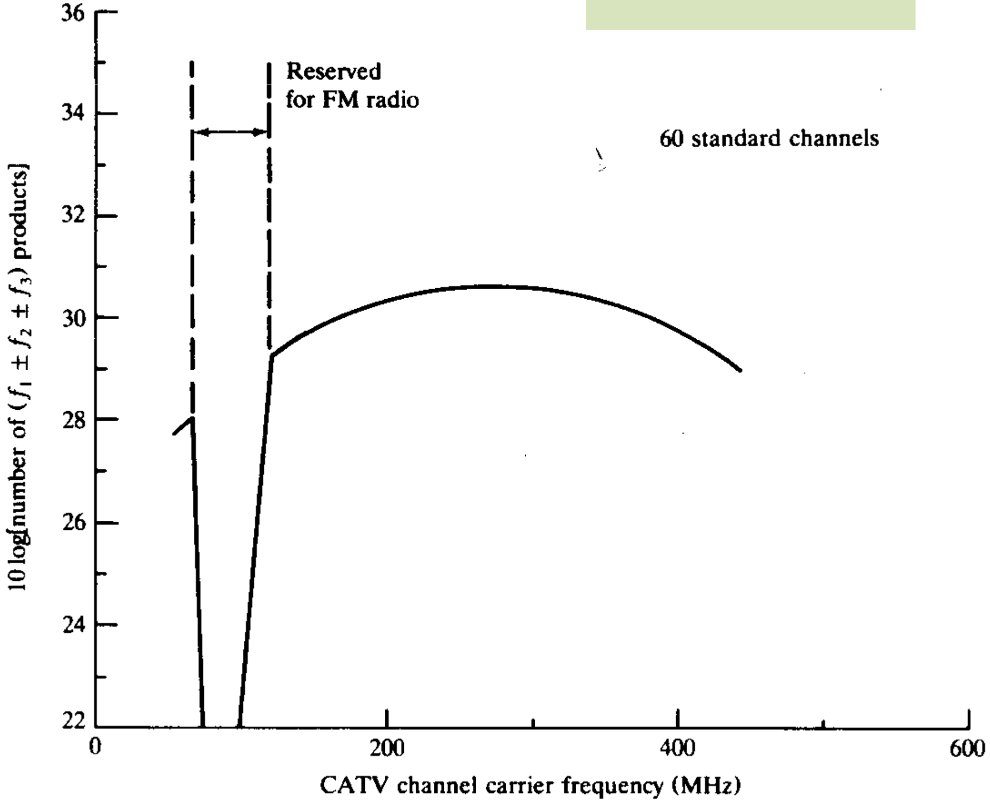
Multichannel Amplitude Modulation (9)

Predicted relative CSO and CTB performance for 60 amplitude-modulated CATV channels in 50-450 MHz



CSO

CTB



Multichannel Frequency Modulation

- The use of AM-VSB signals has a *C/N* or *S/N* requirement of > 40-dB for each AM channel, which places very stringent requirement on laser and receiver linearity.
- FM scheme requires a wider bandwidth (30-MHz versus 4-MHz for AM), but yields a SNR improvement over the CNR.
- The *S/N* at the output of an FM detector is much larger than the *C/N* at the input of the detector. The improvement is given by

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{C}{N}\right)_{in} + 10\log\left[\frac{3}{2}\frac{B_e}{f_v}\left(\frac{\Delta f_{pp}}{f_v}\right)^2\right] + w$$

where B is the required bandwidth, $\mathrm{D}f_{\mathrm{pp}}$ is the peak-to-peak frequency deviation of the modulator, f_{v} is the highest video frequency, and w is a weighting factor used to account for the nonuniform response of the eye pattern to white noise in the video bandwidth.

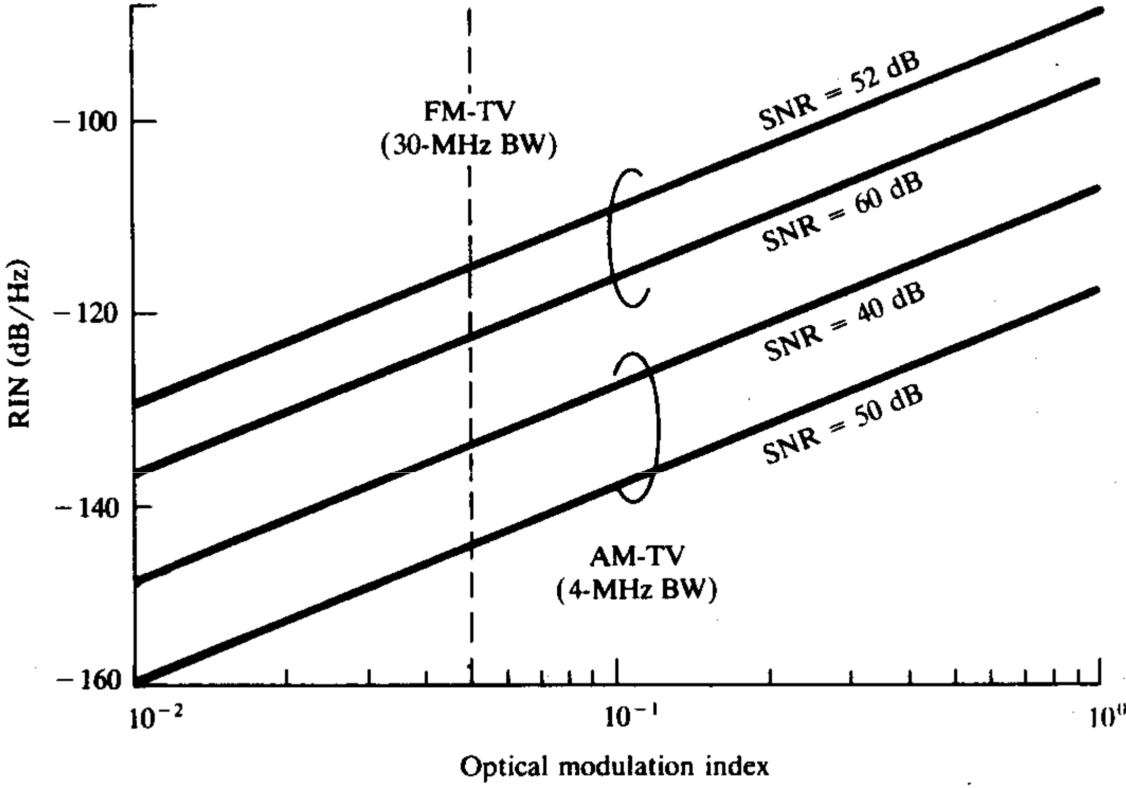
- The total *S/N* improvement is generally in the range of 36 ~ 44 dB.

Multichannel Frequency Modulation (2)

Example 9-5: RIN vs OMI.

Assume that

- RIN noise dominates
- $S/N = C/N + 40$ dB for the FM system
- AM bandwidth per channel = 4 MHz
- FM bandwidth per channel = 30 MHz



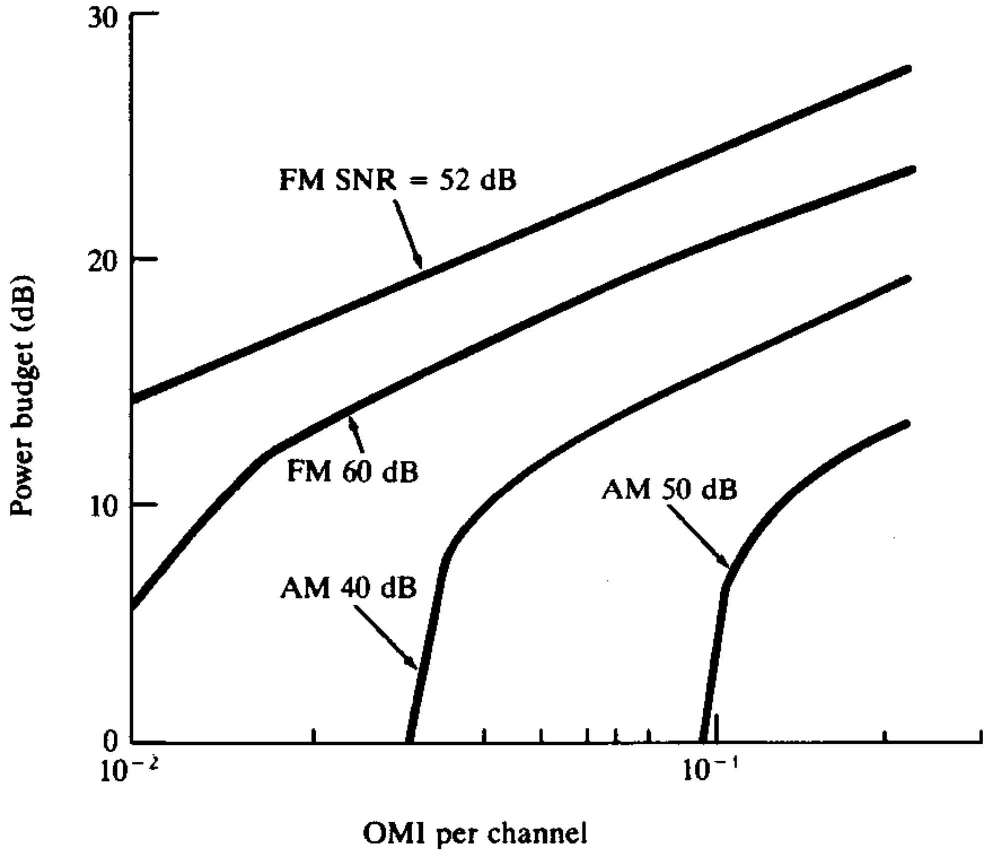
Observations:

- If the per-channel OMI is 5 %, then a RIN < -120 dB/Hz is needed for each FM TV program, requiring $S/N \geq 56$ dB.
- For an AM system a laser with an RIN value of -140 dB/Hz can barely meet the CATV reception requirement of $S/N > 40$ dB.

Multichannel Frequency Modulation (3)

Example 9-6: Power budget vs OMI. Assume that

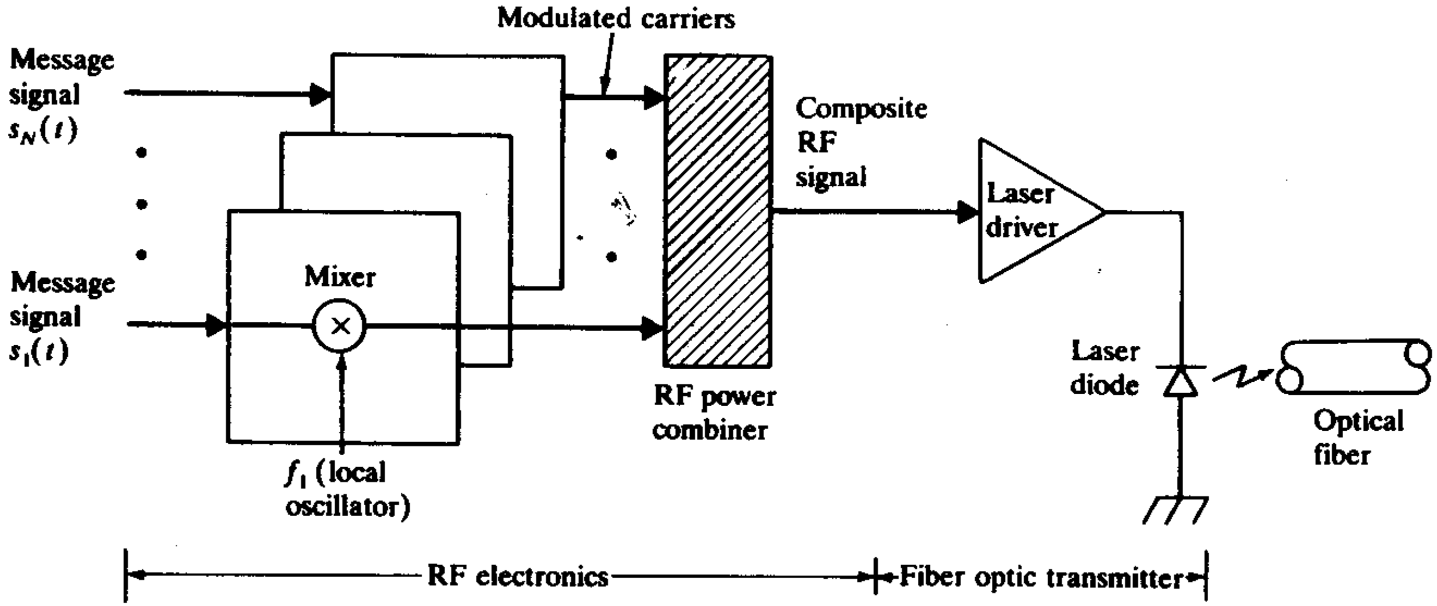
- Laser power coupled into SMF = 0 dBm
- RIN = -140 dB/Hz
- pin receiver with a 50-Ω front end
- Preamplifier noise figure = 2 dB
- AM bandwidth per channel = 4 MHz
- FM bandwidth per channel = 30 MHz



- FM bandwidth per channel = 30 MHz
- Assuming a per-channel OMI of 5 %, the AM system has a power margin of about 10-dB for a 40-dB SNR, whereas the FM system has a power margin of 20-dB for *S*/*N* = 52-dB.

Subcarrier Multiplexing

- The figure below shows the basic concept of an SCM system. The input to the transmitter consists of a mixture of N independent analog and digital baseband signals.
- Each incoming signal $s_i(t)$ is mixed with a local oscillator (LO) having a frequency f_i. The LO frequencies employed are in the 2 to 8 GHz range and are known as the subcarriers.
- Combining the modulated subcarriers gives a composite FDM signal which is used to drive a laser diode.



Subcarrier Multiplexing (2)

- At the receiving end, the optical signal is directly detected with a wideband InGaAs PIN photodiode and reconverted to a microwave signal.
- For long-distance links, one can also employ a wideband InGaAs APD with a 50 to 80-GHz gain-bandwidth product or use an optical preamplifier.
- For amplifying the received microwave signal, one can use a wideband LNA or a *pin*-FET receiver.