Chapter 22

The GMRT Optical Fiber System

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22.1 Introduction

The Giant Metrewave Radio Telescope (GMRT) consists of a distributed array of antennas all connected to a Central Electronics Building (CEB) via optical fiber links. Optical fibers are superior to the more traditional co-axial cables or waveguides in a variety of respects. Optical fibers have lower transmission losses, higher bandwidth and have better isolation against radio frequency interference. More quantitatively, while the loss in co-axial cables are several 10 s of dB/km, the loss in optical fibers is as low as 0.2 dB/km. Further 100 GHz-km bandwidths are routinely achievable in single mode optical fibers, while the achievable bandwidth for co-axial cables is only ~ 20 MHz-km.

The optical fiber link between the CEB and a given antenna has two major functions:

1. Transmission of local oscillator (LO) as well as control signals from the CEB to the antenna, and
2. Transmission of the astronomical signal as well as monitoring data from the antenna to the CEB.

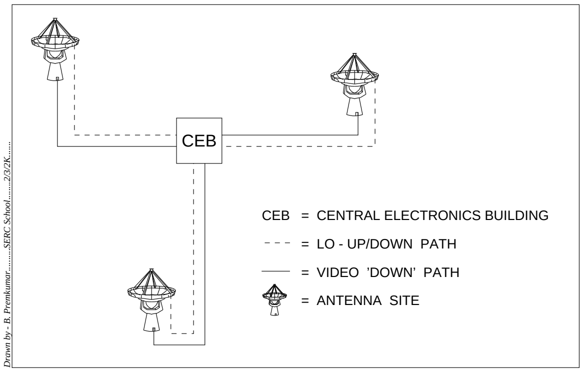

Figure 22.1: Schematic of the optical link at the GMRT. Each antenna is connected to the central electronics building by two fibers, one for the *forward* link, and the other for the *return* link.

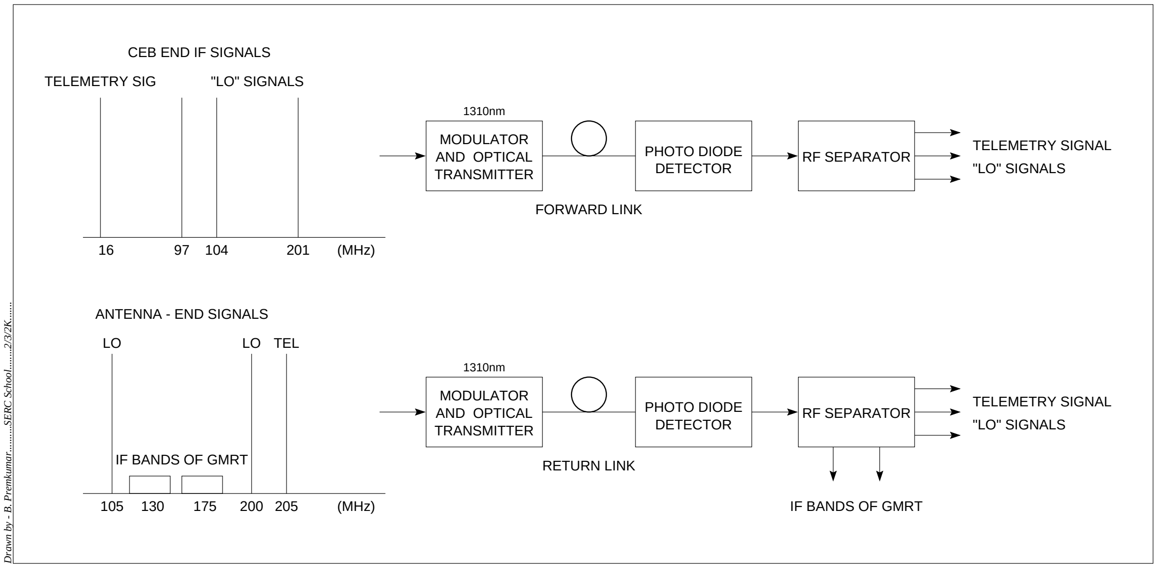

Figure 22.2: Configuration of the GMRT optical communications link. The upper panel shows the *forward* link that takes control signal and LO signals from the CEB to the antenna. The lower panel shows the *return* link that brings the astronomical signal (at the IF frequency) as well as the telemetry and return LO signals from the antenna to the CEB. The frequencies of the various signals transported by the link are also indicated.

As shown in Figure 22.1 there are two fibers between each antenna and the CEB, one of which forms part of the *forward link* and carries the control and LO signals to the antenna, and the other of which forms part of the *return link* and carries the astronomical signal (at the IF frequency, see Chapters 21, 23) and the monitoring data (also referred to as telemetry data) and the return LO[1] back to the CEB. Each link consists an optical transmitter (a laser diode) the fiber itself (which is a single mode glass fiber), and a receiver (a photo diode). A block diagram of the GMRT optical Link is show in Figure 22.2 and the frequencies of the different signals that are transported by the link are also indicated. We now discuss the various elements of the GMRT optical link in some more detail.

22.2 The Laser Transmitter

A block diagram of the GMRT optical transmitter is shown in Figure 22.3. The optical signal that is transmitted down the fiber is generated by appropriately modulating a laser diode, which is essentially a forward biased p-n junction diode (typically InGaAsP). The edges of the p-n diode are cleaved such that they act as mirror resonators. Photons travel between the mirrors and for the wavelengths which bear the following relationship with distance between the mirrors, longitudinal mode oscillations occur:

$$\nu_q = q(c/(2 \times n \times l)) \tag{22.2.1}$$

where q is an integer, l is the length of cavity, n is the refractive index of the medium and ν_q is the longitudinal mode frequency. An active medium within the diode provides positive feedback to these photons thus providing amplification.

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[1] The return LO is useful in measuring the phase stability of the system as well as in correction for the phase

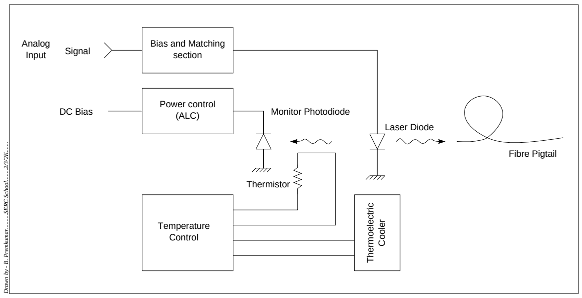

Figure 22.3: Block Diagram of the GMRT optical transmitter.

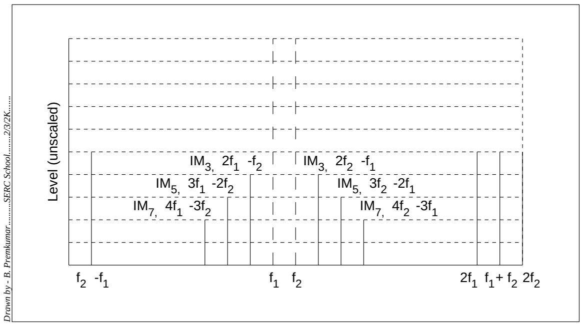

Figure 22.4: The relationship between the frequencies of a few low order inter-modulation products (bold lines) and the the fundamental input frequencies (dashed lines).

The laser used in GMRT is of multi-mode type. The (nominal) peak wavelength is 1300 nm and spectral width is 2 nm (rms). Multi-mode lasers are appropriate for "low" (i.e < 10 GHz) bandwidth applications. At higher bandwidths multi-mode lasers are not acceptable, since they lead to more dispersion and also to *inter-modulation* products. Inter-modulation (IM) products are essentially a particular kind of non linear response. When two pure sine waves are fed to a non ideal device, the output will have additional frequency products that are related to the frequencies of the two input sine waves. These are called IM products of different orders. Figure 22.4 shows a few low order inter-modulation products. The amplitudes for these products is a non linear function of the amplitudes of the input sine waves (see Figure 22.5). The figure also illustrates *gain compression* where beyond a critical input power the output is no longer linearly related to the input, even at the fundamental frequency.

The laser intensity is modulated according to the signal that is to be transmitted, i.e at the GMRT one uses analog modulation. There are two types of analog modulation, *direct* and *external*. In direct modulation the signal is applied directly to an optical carrier generator whose light output varies as per the applied signal. In external modulation the modulating signal is applied outside the device for changing the intensity of the light carrier. In GMRT the simpler direct modulation method is employed.

In the linear regime, the optical power output, P_{opt} by the laser is proportional to the input current i_n, the constant of proportionality is the slope of the characteristic curve and is usually denoted by S.

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introduced during the LO transmission process.

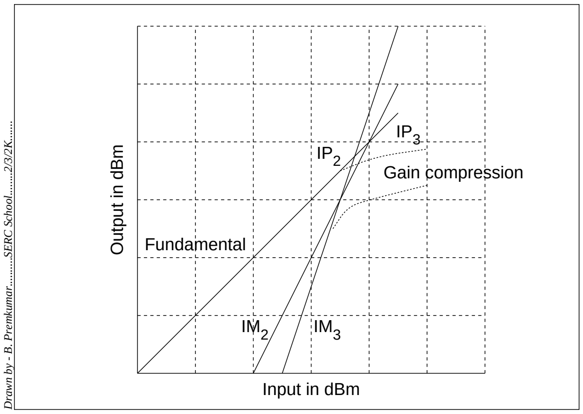

Figure 22.5: Output of a slightly non-ideal optical transmitter showing 2nd and 3rd order inter-modulation products as well as gain compression

22.2.1 Laser Specifications

Rated power o/p : 1 mW @ 51 mA bias current
Threshold current : 28 mA
Peak wavelength : 1306 nm
Slope of the transfer curve : 0.04 mW/mA (appendix 2).
EIN (Eqv. Input Noise) : -137.57 dBm/Hz.

22.3 The Optical Fiber

An optical fiber is essentially a dielectric (silica glass) waveguide consisting of a core and cladding. The core is usually has a circular cross-section (although elliptical or other cross-sections are also used) and is made of doped silica of refractive index slightly higher than that of the cladding (which is made of pure silica). Light waves are guided along the fiber via total internal reflection. If light is launched at an angle greater than the critical angle, the rays are reflected back into the core from the surface separating the core and cladding. The rays travel along the length of the fiber by continuous reflections of this type. Rays launched at different angles travel along different paths (or modes) and arrive at the receiver at different times, leading to *inter-modal dispersion*. Fibers are classified as *single-mode* or *multi-mode* depending on whether they support one or more. Single mode fibers have narrow cores, typically 10νm. Multimode fibers have core dimensions ~ 5 times larger. The number of modes a given fiber can support is characterized by the V number, which depends on the frequency, the core radius and the refractive indices of the core and the cladding.

$$V = \frac{\omega}{c} a \sqrt{{n_1}^2 - {n_2}^2} \tag{22.3.2}$$

where $n_1,\ n_2$ are the refractive indices of the core and cladding, a is the radius of the core and ω is the angular frequency of the light being transmitted through the fiber. The number of modes N is given by $N = V^2/2$. Multimode fibers have bandwidths that are ~ 100 times smaller than single mode fibers and are best suited to short haul applications. In addition to the number of modes supported, the polarization properties of the fiber are also of interest. One can make fibers that maintain the polarization state of the transmitted light by proper choice of core cross-section and refractive index gradient

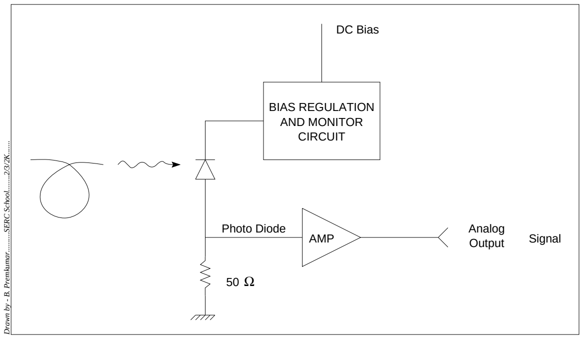

Figure 22.6: Block diagram of the GMRT optical receiver.

across the core and the cladding.

Dispersion is an important characteristic of an optical fiber, it determines the bandwidth and channel carrying capacity of the fiber. here are three kinds of dispersion viz: inter-modal dispersion, material dispersion and waveguide dispersion. Inter-modal dispersion occurs because of the different modes in which the light propagates in the fiber travel different paths. This causes differences in the arrival time of the rays at the receiver and hence a distortion of the signal. Inter-modal dispersion is less in fibers which have a parabolic refractive index parabolic profile in the core region. This change in refractive index causes a change in the light travel time in different parts of the core which partially compensates for the different path lengths. Material and waveguide dispersion are wavelength dependent. Material dispersion arises because of variation in the refractive index of the core material (i.e. silica) across the transmission band. Waveguide dispersion is due to the propagation constant (i.e. the inverse of the group velocity) dependent property of the medium. The derivative of the propagation constant w.r.t frequency is dependent on the frequency itself, even in the absence of material dispersion.

Dispersion affects both the temporal and spectral characteristics of the signals and it is essential to minimize it as far as possible. This can be done by

1. Choosing the 1300 nm window where dispersion is minimum. It may be noted that dispersion for silica fiber is minimum in the 1300 nm band(typically 2 ps/km-nm) compared to that at the 1550 nm band (15 ps/km-nm). However the attenuation is higher in the 1300 nm band (0.31dB/km) than that in the 1550 nm band (0.15 dB/km).
2. Choosing a laser with line-width as small as possible(< 1 nm), like a single longitudinal mode type or DFB laser.
3. Using external modulation. Unlike direct modulation, external modulation does not affect the physical mechanism of the laser and does not introduce spreading of frequency or chirping.
4. Using dispersion compensation. This is essential achieved by proper design of the refractive index gradient across the fiber.

22.4 The Optical Receiver

Photo detection is the process of conversion from optical to electrical domain. A block diagram of the GMRT optical receiver is shown in Figure 22.6. The basic detector is a reverse biased p-n junction diode. In this bias condition a reverse leakage current (the *dark current*) flows. The threshold for detection is determined by the dark current. The other important characteristic of a photo-detector is its *responsivity* R. The responsivity is a measure of the efficiency with which light is converted to electrical current and it is related to the width of the depletion region of the diode and to the spectral response of the receiver. A larger depletion region leads to a better responsivity. PIN diode detectors made of InGaAsP and grown on InP are popular photo-detectors as they have low dark currents and high responsivity. In the case of the GMRT, the detector used has a dark current of 5 nA and R of 0.8 mA/mW.

In order to match the device to the electrical output device, care has to be taken to maintain a wide frequency response and to keep the thermal noise contribution of the detector low. In the case of the GMRT the laser noise is more than the thermal noise contribution of the photo-detector.

22.5 Link Performance

The relation between the power delivered at the output of the detector to the power input to the laser is:

$$P_o = P_i \big[\frac{SRl}{2}\big]^2 \tag{22.5.3}$$

Where S is the slope of the laser diode characteristic curve, R is the responsivity of the photo-diode and l is the loss in the fiber. The total loss is the combination of losses due to attenuation in the fiber, splices, bending of the fiber and couplers. Measurements show that the optical losses of the links vary between 0.3 to 8.7 dB for the various antenna stations.

In addition to this change in signal power level, the link also introduces noise. Noise is introduced by the laser diode, the photo- diode as well as all resistive elements in the signal path.

The laser diode introduces noise due to quantum fluctuations even under conditions of constant bias current. This is called *Relative Intensity Noise* (RIN) and is define as:

$$RIN = \frac{\langle \Delta P^2 \rangle}{\langle P^2 \rangle} \tag{22.5.4}$$

where ΔP are the fluctuations in the laser diode output power, and P is the instantaneous laser diode output power. The laser diode noise is also often characterized by the *Equivalent Input Noise* (EIN) which is defined as $EIN =< \Delta I^2 > R_i$ where ΔI is the input current fluctuation that would correspond to the output power fluctuations ΔP. It can be shown that $\mathrm{EIN} = \mathrm{RIN}(I_{\mathrm{bias}} - I_{\mathrm{threshold}})^2 \times R_i$, where R_i is the input resistance.

The noise generated within the the photo detector is called shot noise. As the name suggests, it is due to the discrete nature of light and its interaction of photons with materials. Shot noise is present in the detector even in the absence of illumination and increases with illumination of the detector with light. All resistive elements contribute to thermal noise. The total noise power(N) is the sum of the laser, shot and thermal noise components. The Signal to Noise Ratio (SNR) of the link can be shown to be

$$SNR = \frac{P_i \big[\frac{srl}{2}\big]^2}{\big[EIN(\frac{srl}{2})^2 + 25e(RP_0 l + I_d) + FkT\big]B} \tag{22.5.5}$$

where F is the noise figure of the detector amplifier, T is the temperature of the resistive elements, B is the bandwidth of the link, I_d is the dark current, P_0 is the average output power of the laser, and e is the electron charge. The analog optical fiber communication system of the GMRT has been designed to ensure a minimum SNR of 20 dB .

In addition to this intrinsic additive noise, there are various other imperfections in the fiber optic link. Discontinuities in the refractive index near the connectors, couplers, bends in the fiber and impurities along the length of the fiber could cause part of the light to get reflected back into the laser. This leads to the formation of a resonant cavity between the discontinuity and the laser hence to ghosts. To overcome this problem, optical isolators and low reflection connectors are used. An optical isolator is a unidirectional device with highly reduced signal transmission in the reverse direction. Low reflection connectors are special devices with refractive index matching and focusing arrangements.

The other important characteristic of the optical link, apart from the SNR is the dynamic range, i.e. the range over which its response is linear. The dynamic range of the GMRT optical fiber link is ~ 14 dB were the input to be purely Gaussian random noise, and ~ 19 dB for quasi-sinosidal input.