OPTICAL FIBRES IN RADIOASTRONOMY.

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ABSTRACT

Within the recently completed Australia Telescope, optical fibres are used extensively to carry wideband IF data, LO reference signals, timing signals and computer communications. This paper discusses the various options considered in the design of the optical fibre system.

1. INTRODUCTION

This paper is an update of a paper given at the IAU symposium 131 in October 1990.

The Australia Telescope (AT) is now operational and is the first radiotelescope to make extensive use of optical fibre technology to carry wideband IF data, LO reference signals, timing signals and computer communications.

Optical fibre is widely used in the telecommunications field primarily because of its low cost, low loss and large bandwidth. The cost of a fibre cable is typically one fifth the cost of coaxial cable of comparable capacity. Loss is typically 0.5 dB per kilometre, the potential bandwidth of single mode fibre is extremely large and fibre does not have to be equalized as does coaxial cable with its steep increase of loss with frequency. An additional benefit in a radiotelescope environment is that optical fibre is immune to electrical interference and also produces no interference. However, optical connectors are less than ideal and the poor signal to noise ratio and linearity partly explain the widespread use of simple digital modulation in most fibre applications.

For a connected interferometer array, the most obvious use of fibres is for the return of IF signals from individual antennas to a central correlator or similar device. Bandwidths in excess of 10 GHz are now quite possible and a bandwidth of around 1 GHz is achieved with readily available components over distances in excess of 10 km.

Another potential use for optical fibres is for the transfer of local oscillator reference frequency signals to all antennas within a round-trip, phase-stabilization system. The lower temperature coefficient and low loss at frequencies around 1 GHz make fibre an attractive medium for this application. Early AT development work pointed to some difficult problems to overcome due to the combination of low loss and high levels of reflection in optical fibre systems. Components are now greatly improved and the phase disturbing mechanisms better understood so that a transfer stability of the order of 1 pS rms (ie. 0.3 degrees per GHz)

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is now quite achievable. Work at JPL (Primus et al 1989) suggest that stability an order of magnitude better is possible with fixed end stations and without connectors. Optical fibre with a very low temperature coefficient is now available and may remove the need for round trip correction in short links (Lutes et al 1989).

Computer links, LANs, timing and other less demanding communication links are other obvious applications. The major advantages are low cost and good electromagnetic compatability.

2. MODULATION

Simple digital amplitude modulation (where the optical carrier is switched on and off) is by far the most common modulation technique and is used within the AT for all applications except LO reference transfer. This form of modulation has the advantage that the cable delay variations can be easily removed by using clock recovery from the fibre and synchronizing bits. Digital modulation implies that the sampler is within the antenna and this can cause some problems due to interference for example.

Analog amplitude modulation suffers from poor signal to noise ratio and often from poor linearity. Frequency modulation of a subcarrier is often used to reduce these effects but at the expense of much reduced bandwidth. Newer components have greatly reduced the reflections which cause fine-structure passband-ripples when using amplitude modulation but reflections at connectors can still cause problems. A delay correction scheme is also usually necessary for analog systems to correct for cable drift.

3. SINGLE MODE OR MULTIMODE ?

Single mode fibre with a diameter of 125 μm and a light carrying core of 10 μm or less is the most widely used type of fibre for wide bandwidth transmission. Terahertz bandwidths are ultimately possible but transmit and receive devices and multiplexers currently limit the bandwidth available to around 20 GHz or lower. The only significant disadvantage of single mode fibre is that the usual butt connectors for this fibre are quite fragile.

Systems using multimode fibre where the core diameter is 50 μm or larger can avoid this problem by using robust expanded beam (lensed) connectors as described later. The major disadvantage of multimode fibre is that it is inherently bandwidth limited due to modal dispersion. However, a bandwidth of 1 GHz over a distance of 2 km (or 100 MHz over 20 km) is now readily achievable. Modal noise (Epworth 1981) can also seriously impair multimode systems.

As with normal copper cables, fibre cables usually contain many fibres protected in slots or tubes within a heavy protective jacket. It is quite possible to have more than 30 fibres in a cable of 10 mm diameter.

4. CONNECTORS

Using optical fibre in a radiotelescopes with movable antennas presents a problem, particularly where this movement occurs regularly. Connectors are usually used in this situation and butt connectors for single mode fibre achieve a typical loss of less than 0.1 dB for a mated pair. Both fibre end faces and alignment inserts are easily damaged by dust and abrasion. This is not a significant problem for the typical telecom fixed link but, in an application requiring frequent disconnection, connector lifetime can be as little as 10 to 50 matings unless adequate care is taken. This care involves a dust free environment and careful cleaning of the connector at every mating. Alternatives to connectors such as trailing cables are cumbersome.

The AT uses expanded beam connectors which use lenses to achieve greater robustness by expanding the light carrying beam exiting from the fibre core to typically 0.5 mm in diameter. The light beam then travels across a small air space at the connector interface before being refocussed into the second fibre core. A moderate amount of dust is no longer a problem and a light wipe is all that is needed for cleaning. Condensation can be a problem but the AT has not yet experienced any such failure even in very wet conditions. These connectors have a typical loss of 1 dB per mated pair and designers of analog systems should also be wary of significant reflections in expanded beam connectors. Until recently, robust expanded beam connectors were only available for multimode fibre.

Fibre connections which do not need to be disconnected can either be butt connected with one of the mechanical splices available or fusion spliced. Fusion splicing is a well developed technique but it does require access to a good fusion splicing machine and these are still expensive. Splice losses are generally much less than 0.1 dB.

5. LIGHT SOURCES AND RECEIVERS

The light-emitting diode (LED) is the simplest light source, it is inherently eye safe and, since it is an incoherent source, it does not produce modal noise in multimode fibre. Unfortunately, the output power is typically only 10 µW and the maximum modulation rate is around 100 MHz.

Semiconductor laser diodes are normally used for the higher speed systems. Output power is usually in the 0.5 to 5 mW range and although bandwidths extend to beyond 10 GHz, devices in the 1 GHz range are more common. Such lasers do not have sufficient power to damage normal tissue but it is possible to damage sensitive eye tissue and it is wise to consider protection measures.

Most lasers are still of the simpler 'Fabri-Perot' construction but distributed feedback (DFB) lasers, which have extremely narrow spectral width, are becoming more commonplace especially for long distance links. However, there is a danger that the improved coherence of these devices may cause them to be more easily disturbed by reflections, especially in short link applications.

The receiving element is either an avalanche photodiode or PIN diode and these are followed by low noise, high gain amplifiers. These amplifiers can be either conventional 50 Ω microwave amplifiers or special purpose transimpedance or FET input amplifiers with equalization. Minimum usable input optical power depends on the actual devices used but is typically -45 dBm for a bandwidth of 10 MHz and reduces to around -30 dBm at 1 GHz bandwidth for a system with 20 dB signal to noise ratio.

Lasers and LEDs are only available at a few wavelengths. The least expensive components are at 0.85 μm and most computer links are at this wavelength. The AT and most telecom and other wide bandwidth links operate at 1.3 μm wavelength where the chromatic dispersion of the fibre is a minimum. This wavelength also has much lower fibre loss and is the usual choice for long, wideband links. At present, the range of specialised components is also best at this wavelength. For very long links, systems operating at 1.55 μm wavelength have the lowest loss, although dispersion can limit the bandwidth unless very narrow spectral width lasers are used.

6. MULTIPLEXING AND CABLING

Most radiotelescope systems will require more than one communication path and some form of multiplexing onto a single or small number of fibres can be considered. Multiplexing can reduce the number of fibres and hence the number of connectors.

If the signals are all digital, then time division multiplexing is common at low bit rates but is more challenging at gigabit rates unless a suitable commercial multiplexer can be found. Multiplexing also requires a much wider bandwidth fibre link.

Wavelength division multiplexing is the equivalent of frequency division multiplexing on a microwave carrier. Several options are possible. Many IF channels could be carried on different optical bearers separated in wavelength by say 10 nm in the 1.3 μm band. This technique is expected to be widely used in future since it has immense bandwidth capability, but few components are readily available. Alternately, one IF channel could use the 1.3 μm band with another IF channel in the 1.55 μm band for which components are available. A third alternative is to multiplex lower bit rate (< 100 Mbit/S) computer links etc. on the same multimode fibre at a wavelength of 850 nm where components are less expensive. The AT uses this approach.

Signals at different wavelengths can flow in opposite directions if necessary, provided that the wavelength-separating demultiplexers are bidirectional. In fact, it should be possible to use the same wavelength in opposite directions on the same fibre using available high directivity couplers and power splitters. However this will present problems unless reflections are kept very low.

For a radiotelescope with movable antennas, there are many more antenna stations than antennas and a cabling strategy must be chosen. The choices are essentially the same as for coaxial cable except that fibre is relatively inexpensive and connectors are more lossy and expensive so that the balance is often tipped towards a system which uses more fibre and less connectors.

The AT uses the simplest cabling strategy where a separate cable runs from each station, with the cables from the many unused stations lying idle. This uses a large amount of fibre and requires some sort of switchboard at the centre to connect to the cables which run to the active stations. An alternative is to have a 'trunk' cable and use links at each unused station. This will require many robust connectors in series. The loss is likely to be around 1 dB per station and this may be unacceptable if there are many stations. The use of couplers at each station is another alternative but the loss is higher and the cost is usually also higher.

7. THE AUSTRALIA TELESCOPE SYSTEM

The system chosen for the 3 km AT subarray uses one four fibre cable from each station. Each fibre conveys a single, digitized IF channel to the central site at a wavelength of 1.3 μm. Manchester coding was chosen since, although it is wasteful of bandwidth, it is easier to implement at these high rates than alternative codes. Manchester coding converts the 512 Mbit per second sampler output rate to a 1024 Mbit per second rate on the fibres.

Wavelength multiplexing is used to carry bidirectional computer links and timing signals at a wavelength of 0.85 μm on the same fibres. Wide bandwidth multimode fibre avoids the connector problems of single mode fibre. The total link loss due to the 2 km cable length, connectors, multiplexers and splices is around 10 dB at 1.3 μm and 15 dB at 0.85 μm.

Each station post uses a 4-way, expanded beam, military style connector, having 1 dB typical loss. A patch panel exchange at the central building uses inexpensive, expanded beam connectors. The graded-index multimode fibre has a 50 μm core , 125 μm glass cladding and an acrylate buffer. There is a total of 40 km of 4-fibre cable which is 12 mm in diameter, uses 'kevlar' reinforcing and a rigid nylon jacket. Slotted core construction was used for the underground cable and tight buffer construction for the vertical runs. This avoids excessive weight on the fibre ends.

Laser sources are used for the high bit rate 1.3 μm channels and LED sources at 0.85 μm. 1.3 μm receivers use APD detectors and simple 50 Ω amplifiers. The 1.3 μm system has now been operating for two years with excellent reliability. Bench tests showed a link bandwidth of 1 GHz and an error rate of 1 in 10^{15}.

A fixed antenna, which is 5 km from the central site, is used to extend the baseline to 6 km. Single-mode fibre is being used for this link due to the longer distance and the reduced connector problem. Multiplexing is not used for this link. A separate pair of fibres has also been installed for the distribution of LO reference to this site as described below.

Optical fibre is also being used for many short links within antennas and buildings to reduce interference and cost. For example many of the interconnections into the correlator screened room are to be converted to optical fibre.

The AT uses single mode fibre to convey LO reference signals to the 6 km site. Tests carried out on a round trip system for LO reference transfer, indicated that separate fibres for the forward and return paths do not degrade performance, provided that they are closely coupled thermally (Sarma 1988). In fact, performance of a single fibre test system was slightly worse, due to the inadequate isolation and higher reflections in the directional couplers necessary in such a system.

A 160 MHz reference signal is sent along one fibre to the antenna. A narrow bandwidth phase-lock loop at the antenna recovers the signal and produces a very low phase noise signal for use within the LO systems. Some of this reference signal is also sent back along a second fibre to the central site and compared with the original signal in a precision phase meter. From any measured phase change, an appropriate correction is calculated and applied to the antenna LO phase rotators.

8. FUTURE TRENDS

Probably the only certainty is that the usage of optical fibre will continue to increase at a fast rate. The bandwidth of optical fibre systems has rapidly increased so that 10 GHz systems should become more commonplace. Direct increase much beyond this will be slower due to the cost and difficulty of using mm-wave devices. However, other methods of obtaining more use of the potential bandwidth, such as wavelength multiplexing, are likely to gain ground. For example, it may ultimately be possible to multiplex more than 100 channels each of 10 GHz on a single fibre. Coherent detection still appears to be a long way from large scale commercial use but this would help to make multiplexing easier and improve the signal to noise ratio of analog systems.

The cost and availability of optical components should continue to improve but the cost of the optical fibre itself has probably bottomed. Specialised fibre, such as the low temperature coefficient fibre recently released by Sumitomo, may soon become more commonplace and hence less expensive. Optical switches, amplifiers, filters and test equipment are still quite crude, expensive or unobtainable. The future should see a drive to improve these components, making the development of optical switching systems and ultimately optical signal processing and computing systems possible.

9. REFERENCES

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Discussion:

Radhakrishnan:
What is the device used for wavelength demultiplexers?
Young:
The devices used are optical diplexers – essentially grating filters. They are quite compact and rugged and are not expensive.

Marson:
Why didn't you bring the RF back on the fibre and so avoid the need for LO transmission to each antenna?
Young:
This is not yet possible for frequencies above 20 GHz and is very expensive above a few GHz. However this approach has a lot of merit and is being considered for antennas operating below 3 GHz.