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LONG DISTANCE WIDEBAND OPTICAL FIBRE LINKS FOR ACCELERATOR SYNCHRONIZATION

H.H. Beger, D. Boussard
European Organization for Nuclear Research (CERN)
Geneva. Switzerland

1. Introduction

The proper performance of a large scale accelerator complex like the CERN network of machines, requires the transmission, over long distances, of precise timing pulses. In most cases the timing pulses are derived from a master clock (usually the RF frequency), and therefore the ultimate time accuracy of the pulses is determined by the quality of the transmission of the clock frequency itself. A similar problem arises when several accelerating stations are distributed around a large accelerator[1,2], or when two machines need to be synchronized RF-wise. In all cases the transmission of a CW wave in the frequency range of several hundred MHz over distances up to several kilometres is the key to a proper synchronization.

The classical solution, using coaxial cables, is getting more and more difficult and costly, as the frequency and the length of the link increase. The attenuation of coaxial cables, which rises with the square root of the frequency, imposes the use of intermediate amplifiers. This leads to additional cost, complexity and time jitter.

In this context the use of optical fibres as transmission media offers an attractive alternative[3], and indeed a 4 km link was installed in 1978 between the CERN SPS and its injector for the purpose of synchronizing the two machines. We shall report here the technical performance of this particular link in terms of frequency response, signal to noise ratio and long-term stability.

2. The SPS-PS optical fibre link

This link, which joins the SPS RF plant to its injector has two independent channels. One is used to transmit the SPS revolution frequency pulses (repetition rate 43 kHz, pulse width 15 ns, rise time 3 ns), the other carries the SPS reference RF frequency at injection (199.525 MHz in the high intensity mode, 200.265 MHz in the collider mode). At the PS receiving end the revolution frequency pulses are resynchronized with the transmitted RF frequency in order to achieve the best time accuracy (both trains, RF and revolution, are synchronous at transfer). The two channels are identical and can be easily interchanged.

The connecting cable, which is made by Siecor, is installed over most of its 4 km length in plastic tubes buried in the earth. At the time of installation the cable was delivered on bobbins in lengths of 1.1 km, and four splices were necessary along the cable path. The cable contains two fibres and two steel wires as reinforcement; its outer diameter is only 8 mm.

The fibres are made by Corning; they are of the graded index type with a core diameter of 62.5 µm and a cladding diameter of 125 µm. The operating wavelength of this multimode fibre is around 850 nm (near infrared region). At this wavelength, the optical attenuation is about 2.5 dB/km. The connections with the emitter and the receiver are made using 4 mm diameter Siecor plugs.

At the transmitting end, we have chosen a commercial module (General Optronics) containing a Ga As/Ga Al As laser diode.

Compared to a light emitting diode (LED) the laser provides a higher optical power, a faster speed and a much better spectral purity, which are needed for this application.The laser diode (multi-longitudinal, single transverse mode type) is directly coupled to a piece of fibre; it provides an optical output power larger than 1 mW at 850 nm wavelength. The emitting laser module provides cooling of the diode by a Peltier element, as well as internal optical power regulation. The optical output of the transmitter can be amplitude modulated, up to very high frequency (> 1 GHz) by simply controlling the laser diode current (above the coherent emission threshold).

The receivers are built around avalanche photodiodes C30921E from RCA. Temperature compensation and diode protection are provided. The preamplifiers have been specially designed to match the transmitted signals (200 MHz CW wave and 43 kHz pulses).

However, during the measurements described below, the photodiodes used at the receiving end, either fast PIN diodes (HP 5082-4205) in the case of high optical flux, or avalanche diodes (C30921, RCA), were directly driving the 50 Ω input impedance of a commercial low noise, large bandwidth (> 1 GHz) preamplifier.

Avalanche photodiodes are more sensitive (~ 50-100 A/W) than PIN diodes (~0.5 A/W), but are more delicate to use. Their speed and sensitivity depend on the operating voltage (~ 200 V), which must be close to the avalanche region.

3. Overall transfer function of the link

The properties of the laser diode, the optical fibre, and the receiver determine the overall transfer function of the link. The response of the laser-receiver combination (Fig.1a) can be determined by connecting them by a short piece of fibre. It shows no rapid fall off up to 1 GHz; the observed gain fluctuations are presumably due to uncorrected electrical resonances. In the following curves showing the fibre response (Fig. 1b), the laser-receiver transfer function has been taken equal to unity.

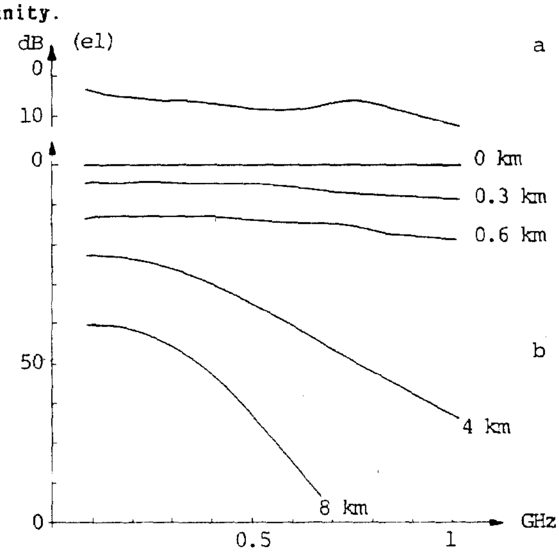

Fig. 1 Laser-receiver (a) and fibre (b) transfer functions

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The attenuation of light in the fibre (~ 2.5 dB/km) and the various connections and splices determines the low frequency signal strength. As the current in the photodiode is proportional to the optical power, the attenuation of the electrical signal goes as the square of the optical attenuation. Indeed, an average electrical attenuation of 5 dB/km is measured (Fig. 1b). The dispersion of the measurements is due to the effect of the various, not exactly identical, connectors.

At higher frequencies, the dispersion of the fibre (several modes with slightly different velocities can propagate simultaneously in the optical waveguide), combined with the spectral width of the laser, deteriorates the transmission. This explains the fall off observed on the gain curves for the 4 km and 8 km links.

The corresponding degradation of pulse shape (rise time ≈ 2 ns) after an 8 km trip is illustrated on Fig. 2. The time delay between input and output pulse corresponds to a group velocity of 0.7 c.

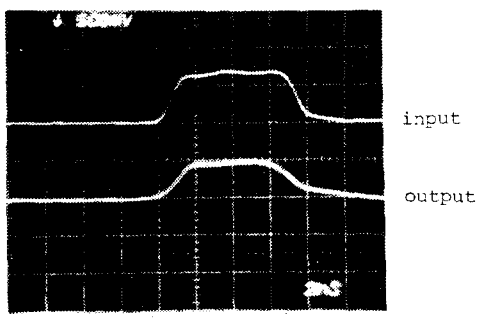

Fig. 2 Pulse transmission over 8 km (2ns/div)

4. Noise performance

The quantum fluctuations of the light emission of a semiconductor laser is given by theory[4]. The essential features are a large peak at the onset of coherent emission (threshold current) and a resonance in the microwave region (several GHz). The noise properties of the laser are described by the relative intensity noise (RIN) parameter[4] which is the ratio of the fluctuating power to the coherent optical power.

Using a short fibre connection between the laser and the receiver we tried to measure the RIN parameter of our emitter. It turned out that the measured value was two orders of magnitude larger than what was expected from theory ($\sim 3 \times 10^{-13}$/Hz instead of $\sim 10^{-15}$/Hz), and showed no strong dependence with the laser diode current. It is very likely that the emitter noise is rather determined in our particular case by the fibre coupling and subsequent mode selection[4]. The spectrum of the noise, measured by a spectrum analyzer, is rather flat (up to 1 GHz), except in the case of a bad fibre connection.

In the vicinity of the RF reference frequency the short term stability of the elements of the link become dominant and the noise spectral density, measured by phase comparison between two identical channels, shows a rapid increase.

When the semiconductor laser is connected to a long optical fibre, which is a purely passive element, one would simply expect that the laser noise should be attenuated like the useful signal (~5 dB/km), leaving the signal to noise ratio constant. This is in fact, not true: the noise level is only attenuated by about 2.2 dB/km (Fig. 3) We attribute this effect to the so-called "modal noise"[5]. It could be considered as the result of a random exchange of modes of oscillation of the laser (or a random FM modulation), which is revealed by the dispersive properties of the long optical fibre and its imperfections.

At the receiving end, two sources of noise must be considered: the well-known thermal noise of the load resistance (and amplifier), and the detector noise. The latter is always negligible for PIN diode receivers, because of their low sensitivity.

For avalanche photodetectors, we can measure their noise current using a white light source giving the same d.c. current in the detector. Note that the dark noise current of the detector is always unimportant because we always want to work with a rather high optical flux[6].

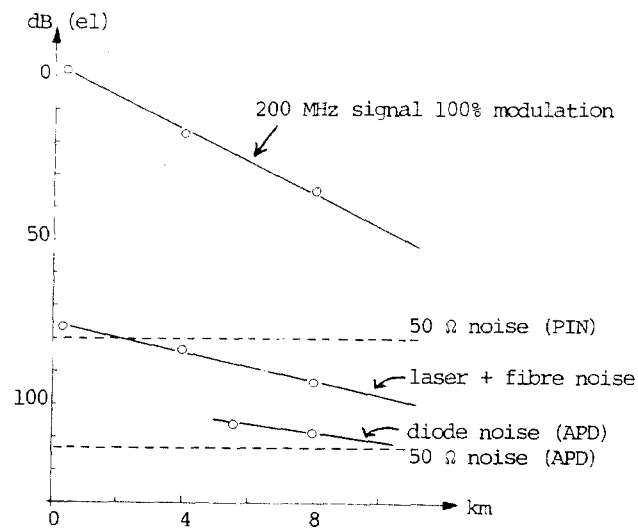

Fig. 3 Relative signal and noise levels (10 kHz BW)

Fig. 3 shows the signal and noise levels which can be obtained using the technology described here, as a function of the link distance. Except for short distances, PIN diode receivers are not recommended, if signal to noise ratio is at a premium. On the other hand, the receiver noise, with avalanche photo-diodes, only becomes important for very long distance links (> 15 km). For most applications, the modal noise (laser and fibre combination) is dominant and determines the overall noise properties of the link.

The spectral characteristics of the noise, in the vicinity of the reference frequency, obtained by phase noise measurement techniques, are displayed in Fig. 4. For a large frequency offset (> 10 kHz) we find the same broadband noise as obtained by direct spectral analysis, whereas closer to the carrier the noise spectral density increases due to the imperfect short-term stability of the components. For comparison purposes, the phase noise spectrum of a very high quality signal generator (HP 8662) is also displayed in Fig. 4. Another interesting comparison is the following: in the collider mode of the SPS, RF phase noise at the synchrotron frequency is of prime importance for beam lifetime[7]. Following noise measurements made on the collider, the present 4 km link would cause the beam lifetime to be limited to about 50 hours were it to drive the RF cavities directly.

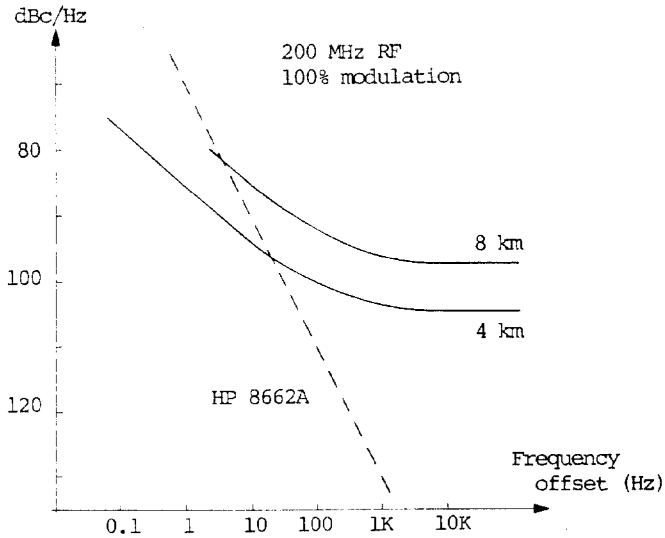

Fig. 4 Close to carrier noise

5. Long-term phase stability

The sensitivity to temperature changes is the essential cause for long-term drifts in a synchronization link[8].

The temperature coefficient of the optical fibre itself has been determined directly. 200 MHz phase variation measurements have been carried out, the 300 m of cable being installed in a temperature controlled oven, leading to a phase variation of 3.6° RF/km/°C. This gives a temperature coefficient of the fibre delay of 10 ppm/°C, which corresponds quite well with the temperature coefficient of the refractive index of vitreous silica (6.8 ppm/°C), responsible for the propagation velocity of the fibre. As a matter of comparison, compensated coaxial cables present a temperature coefficient in the range of 2 to 7 ppm/°C.

The effective overall phase variations of the 4 km SPS-PS link have been measured for a change in the outside temperature of 11.5°C within 18 hours. At 200 MHz, the phase change was 9° RF. As at least 3/4 of the total length of the fibre optical cable lie in narrow plastic tubes about 1 m below the earth's surface the temperature effect is rather small. By measuring the steel wires resistance, it is even possible to monitor the cable temperature and correct for its variations. The sensitivity of our laser transmitter to changes in ambient temperature is about 2° RF/°C.

6. Economical aspects

The price of an optical cable with fibres of a quality similar to that used in the CERN SPS-PS link can be roughly estimated in 1983 as P(SwF/m) $\simeq$ 5(1 + n) where n is the number of fibres up to n = 6.

The corresponding prices for low attenuation "Flexwell" type coaxial cables are:

P(SwF/m) = 18 for 7/8" diameter cable
P(SwF/m) = 36 for 1 5/8" diameter cable

For long distance links, the economy made on the cable price using fibre optic solution quickly outweighs the extra cost of the transmitter and receiver units (receiver $\simeq$ 5 KSwF, laser module $\simeq$ 14 KSwF, plus 1.75 KSwF/year due to the laser diode lifetime, longer than 10^4 hours).

The above data show that additional spare fibres for future needs may be installed from the beginning with relatively little extra cost. Moreover, "double window" fibres which are now available at little extra cost (10%), offer two usable wavelengths (850 nm and 1300 nm) and therefore permit future extensions (higher bandwidth at 1300 nm wavelength, or frequency multiplexing). Fibre optic cables, which can now be obtained in lengths of 2.2 km may be laid directly into the earth together with, for instance, high voltage cables, without a need for any further precautions.

7. Conclusions

The presently used 850 nm wavelength multimode fibre technology offers a reliable, commercially interesting solution for accelerator synchronization in the several hundred megahertz range. The disadvantage in an accelerator environment is that fibre optic cables cannot be used in radioactive areas[9]. On the other hand, the problems associated with unpredictable electromagnetic interference (fast pulsed magnets, RF power stations, etc) which we met previously with electrical links, are completely avoided by the optical solution. To obtain the best signal to noise ratio, it is important to take great care of the optical connections, to prevent mode selection and the corresponding increase of modal noise. Other applications of the fibre optic technology in the accelerator field can also be envisaged, for instance delay lines having a very large time-bandwidth product.

Several steps towards larger bandwidths and better signal-to-noise ratios can be envisaged: operation in the 1300 nm spectral window, where the fibre dispersion is very low, and the use of newly developed monomode single polarization fibres. In the far future heterodyne and coherent detection[10] may further improve the quality of the receiver.

Acknowledgments

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References

1. P. Bramham, RF phase reference distribution in LEP. CERN LEP Note 203.
2. H.D. Schwarz, J.N. Weaver, The RF reference line for PEP. IEEE Trans. on Nucl. Science, Vol NS26 No.3, June 1979, p.3956-3958.
3. H. Beger, J. Bosser et al., Beam observation via an Optical transmission system. Siemens Telecom. Report, vol 2. No. 3, Sept. 1979 p. 164..168.
4. H. Jäckel, Lichtemissionsrauschen... 8 GHz, Diss.ETH Zürich No. 6447, 1979.
5. R.E. Epworth, Modal noise, causes and cures, Laser Focus, September 1981.
6. D.W. Bechtle, S.A. Siegel, Microwave frequency optical links, Fiberoptic Technology, Jan. 1983.
7. D. Boussard, G. Dôme, C. Graziani, The influence of RF noise on the lifetime of bunched proton beams, 11th Int. Conf. on High Energy Accelerators, Geneva, 1980, p.620.
8. G. Lutes, Optical fibre applications in the NASA deep space network, Fiberoptic Technology, September 1982.
9. H. Beger, Radiation induced attenuation in some communication glass fibres around 850 and 1060 nm, CERN report SPS/ARF/77-21.
10. T. Okoshi, Heterodyne and coherent optical fibre communications; Recent Progress, IEEE, Vol MTT 30 No. 8, August 1982, p.1138-1148.