ADVANCES IN OPTICAL TIME-DOMAIN REFLECTOMETRY

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1. Introduction

In recent years, optical time-domain reflectometry (OTDR)[1] has progressed from a laboratory experiment to a technique in everyday use by manufacturers and users of optical fibres. The principal attraction of the technique is its ability to give, non destructively, a good indication of the fibre-loss uniformity and therefore to reveal any localised defects in the fibre. It has also been employed as a means of measuring accurately fibre[2] and splice losses[3], and of studying the longitudinal variation of fibre parameters[4,5].

Briefly, OTDR involves the launching of a short pulse of light into the fibre. As the pulse travels along the fibre, its energy is lost in part to Rayleigh scattering. Some of the scattered light is recaptured in the backward direction and guided towards the launching end where it may be detected. The signal obtained takes the form:

$$P_s(t) = P_o W \eta(z) \exp\left[-\int_0^z 2\alpha(z)dz\right] \qquad (1)$$

where the time and position variables t and z are related by $z = v_g t/2$ (v_g is the group velocity). $P_o W$ represents the forward pulse energy, $\alpha(z)$ the local attenuation and $\eta(z)$ the backscatter factor. $\eta(z)$ depends on the fibre waveguide and scattering properties and varies from typically 300 W/J for multimode fibres[6] at 850nm to 10 W/J for single-mode fibres at 1300nm[7,8].

It is clear from (1) that a backscatter signal will not in general give the local fibre attenuation directly since any longitudinal change in the rate-of-decay of $P_s(z)$ could be caused equally by variations of $\eta(z)$ or of $\alpha(z)$. Nevertheless, the mere presence of a non-uniformity normally provides most of the information required and if the measurement is repeated from the opposite fibre end, the effects may be separated unambiguously[4,5]. This paper will review the development of OTDR with particular emphasis on long range single-mode measurements at 1300nm and beyond.

2. Performance Criteria in OTDR

Dynamic range is the single most important criterion of the performance of an OTDR. It is a measure of the fibre loss through which the backscatter signal may be measured to a given accuracy and is expressed in "dB one-way". Although definitions abound, that preferred by the author, particularly for long wavelength systems, is the range at which the signal from Rayleigh scattering becomes equal to the r.m.s. noise.

The spatial resolution of an OTDR depends on the ability of the instrument to respond to an abrupt change of backscatter signal along the fibre and is determined by the convolution of the probe pulse with the impulse response of the optical receiver and data-acquisition equipment. At high resolution, the probe pulse energy is reduced and the noise-equivalent power of the receiver is increased; both effects lead to a reduction in the signal-to-noise ratio. A strong trade-off thus exists between the dynamic range and the spatial resolution of the measurement, and equipment specifications must be considered with this point in mind. Moreover, resolutions quoted in fact frequently refer to the sample separation of the data acquisition electronics rather than to the system analogue risetime.

In addition, the design of an OTDR is influenced by the requirement for portability and ruggedness which usually dictates fairly simple optical designs,the use of injection lasers and precludes any significant cooling of the detector. The wavelength of the probe pulse must be close to the fibre operating wavelength if valid attenuation measurements are to be obtained and to avoid spurious wavelength dependent effects such as the second-mode cut-off loss peak or the microbending edge in single-mode fibres.

As a point of reference, commercially available OTDRs at 850nm typically use a semiconductor laser source, a silicon avalanche photodiode detector (APD) and an all-fibre directional coupler. Typically the dynamic range is 25dB one-way for a resolution of 10m.

3. <u>Operation at Long Wavelength and with Single-Mode Fibres</u>

Pulsed sources for OTDR at 1300nm are not so readily available as at 850nm; their output power is lower and their reliability and temperature stability are worse. Moreover, the silicon APD, an almost ideal detector, does not respond at 1300nm and no other material has shown a similar performance. Germanium APD's are particularly at a disadvantage because, in the bandwidths of interest, their leakage current severely limits the receiver sensitivity. Presently none of the commercially-available APD's can compete at 1300nm with PIN diodes, although some of the laboratory quaternary devices would provide a small improvement in receiver sensitivity.

Additional difficulties are encountered in the design of single-mode reflectometers. For example, the power available from single transverse-mode injection lasers is low and efficient launching into single-mode fibres is difficult owing to the ellipticity and astigmatism of the laser output. Moreover, the backscatter factor is lower in these fibres than in multimode fibres at the same wavelength. The design of single-mode OTDR's must also avoid any polarisation sensitivity in the return optical path, which would lead to an unwanted modulation of the backscatter signal in accordance with the local fibre birefringence.

4. Long-Range Single Mode OTDR at 1300nm

Much work has been devoted recently to the development of OTDR systems for testing single-mode communications at 1300nm and beyond. In this application, the minimum requirement is to detect a break within a repeater span (25dB of fibre loss at 140 Mb/s). A spatial resolution of 100m is usually adopted which is sufficient to determine with certainty the fibre section at fault. There is an overwhelming need for the equipment to be portable and rugged which precludes, for example, the use of high power lasers and cryogenic detectors. In practice, only low-noise analogue direct detection and heterodyne detections are serious contenders.

In the first approach[9,10], a PIN photodiode operated at room temperature is used together with an ultra-low-noise FET-input preamplifier; the receiver sensitivity reported is 30pW before averaging. Multichannel digital averaging allows a further improvement in sensitivity to 30fW in a measurement time of 20 min.

With a semiconductor laser, a dynamic range of 30dB one-way has been obtained, the highest value reported to date. The sensitivity of this receiver matches that of a photon counting receiver using a Ge APD at 77K[11].

In heterodyne detection[12,13], the probe pulse and hence the backscattered power is frequency-shifted with an acousto-optic deflector (AOD) and mixed on the photodiode with an unshifted portion of the source power, which is used as a local oscillator. A backscatter signal is obtained at the intermediate frequency (IF), equal to the frequency shift of the AOD. The detected signal is proportional to the product of the backscatter and local oscillator (LO) electric fields. With sufficient LO power, the signal at the IF can be made large compared with the receiver noise. A coherent backscatter receiver can in principle be two orders of magnitude more sensitive than a direct detection front-end. However, this scheme requires the use of extremely narrow linewidth sources (i.e. a spectral width of the order of the IF bandwidth). Apart from the practicalities of producing a 1MHz linewidth portable laser, the output power of such sources is usually substantially lower than that available from unstabilised lasers. This offsets at least in part the sensitivity advantages of the coherent detection scheme and the best results published to date[13] have failed to match the dynamic range performance of direct detection, although a receiver sensitivity better by a factor of 4 has been demonstrated. Coherent detection suffers from its intrinsic sensitivity to the state-of-polarisation of the backscatter signal and to the speckle-like noise associated with the use of a highly monochromatic source[14].

5. Conclusions

Research into both coherent and direct-detection long-range OTDR systems is active and it is clear that further improvements will be achieved; these will result in part from the availability of better devices namely, higher power, narrower linewidth lasers for coherent detection and low-leakage current APD's for direct detection. Progress is rapid in both of these areas and it is not yet clear which approach will prove to be the most effective in practical instruments.

Finally the use of OTDR has spread into new areas and recently it has been applied to the development of distributed sensors, an area which shows considerable scope for innovation in optical time domain reflectometry.

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