Spectral filters for digital fibre-optic communication systems

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Abstract. With a proper choice of the spectral filter to be used with an LED fibre-optic digital communication link, a substantial increase in information pulse rate can be achieved, when the system is bandwidth limited due to material dispersion. The optimum filter bandwidth depends on the fibre length, attenuation, dispersion and on the LED optical power.

A 60 Å filter would increase the maximum pulse rate from 150 to 800 Mb/s for a 1 km length of fibre with attenuation of 8·6 dB/km and coupled optical power of 100 μW. A power reduction penalty of about 13 dB results.

1. Introduction

Fibre-optic systems tend to be most attractive for digital transmission at communication rates per fibre of the order of 100 Mb/s [1]. However, when light-emitting diodes (LEDs) are used as optical power sources [2], dispersion over their broad spectral emission width limits the pulse rate [3, 4].

Recently, Stewart examined the wavelength filtering effects in multi-mode fibres and proposed that the use of deliberate filtering would result in substantial bandwidth improvements [5].

Here, analytical expressions are obtained for the dependence of the optimum filter bandwidth and the corresponding increase in information pulse rate on other system parameters. Numerical results of filter choice for a practical fibre-optic link are presented.

2. Analysis

2.1. *The received filtered power*

Figure 1 illustrates a block diagram for a digital fibre-optic communication link. An interference filter with rectangular pass characteristics, as shown in figure 2, is inserted in the link.

The spectral distribution of the output of an LED may be written as [6]

$$\phi(\lambda) = (P_0/\sqrt{(2\pi)}\sigma_\lambda) \exp[-0{\cdot}5(\lambda-\lambda_0)^2/\sigma_\lambda^2], \tag{1}$$

where P_0 is the output power of the LED coupled to the fibre, and $2\sigma_\lambda$ represents the spectral width of emission. The received optical power may be expressed as

$$P_r = \int_{-W/2}^{W/2} T_0\,\phi(\lambda)\exp(-\alpha L)\,d\lambda, \tag{2}$$

where α is the attenuation constant of the fibre in neper/km and is assumed constant within the filter bandwidth W; L is the fibre length; and T_0 is the transmissivity of

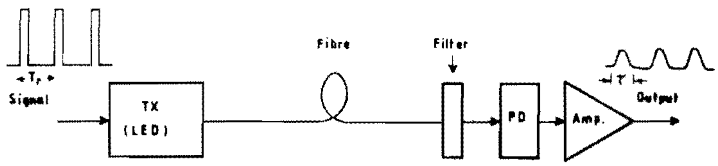

Figure 1. A block diagram of a digital fibre-optic communication link.

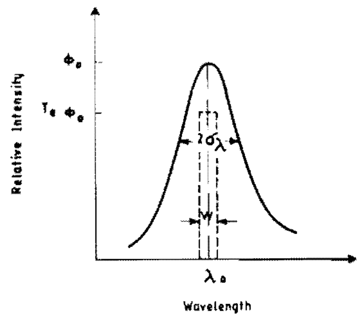

Figure 2. The transmission characteristics of the filter as compared with the spectral distribution of the output of an LED.

the filter. When W is sufficiently small compared to $2\sigma_\lambda$, then from equations (1) and (2) one obtains

$$P_r = T_0 P_0 W \exp(-\alpha L)/\sqrt{(2\pi)}\sigma_\lambda. \tag{3}$$

When a silicon avalance photo-diode (APD) is used, then the received signal power is related to the signal-to-noise ratio (SNR) by [7, 8]

$$\mathrm{SNR} = \frac{(e\eta/h\nu)^2 P_r^2 G^2}{2eB[I_d + (e\eta P_r/h\nu)]G^{2\cdot 5} + N_{th}}, \tag{4}$$

where G is the avalanche current gain, η is the quantum efficiency; $h\nu$ is energy per photon, I_d is the detector dark current; N_{th} is the thermal noise; B is the amplifier bandwidth; and e is the electron charge.

When I_d is sufficiently small, and with an optimum choice of G, equation (4) simplifies to

$$\mathrm{SNR} = \eta P_r / 2\cdot 5\, B h\nu\, G^{1/2}. \tag{5}$$

The received power must achieve the desired SNR corresponding to the allowed bit error rate [9].

2.2. *Spectral filter bandwidth*

When low-loss fibres are used, the fibre-optic system may be bandwidth limited, owing to dispersion, rather than power limited. Dispersion causes optical pulses to broaden as they propagate along the optical fibre. The resultant overlap between adjacent pulses limits the pulse rate, and hence the useful transmission bandwidth of the fibre. Basic mechanisms of dispersion are the wavelength dispersion in the bulk glass and the group velocity spread between the propagating modes [6].

In a graded-index multi-mode fibre the modal group velocity dispersion is decreased by refractive index gradients in addition to mode coupling [10]. Then, the spreading in the received pulses is dominated by the material dispersion [11]. If the pulse spreading is not allowed to exceed half the pulse repetition period, then the filter bandwidth must satisfy

$$WBL = 0{\cdot}5\ \lambda^2 c/n^2\ (dV_g/df), \tag{6}$$

where n is the refractive index of the fibre; dV_g/df the group velocity dispersion; and c the velocity of light.

Combining equations (3), (5) and (6) one obtains

$$W^2L = \frac{3{\cdot}13\, h\, c^2\, \lambda\, \sigma_\lambda\, G^{1/2}\, \mathrm{SNR}\exp(\alpha L)}{\eta n^2\, (dV_g/df)\, T_0\, P_0} \tag{7}$$

and

$$B^2L = \frac{\eta\, \lambda^3\, T_0\, P_0 \exp(-\alpha L)}{5\sqrt{(2\pi G)}h\, n^2\, \mathrm{SNR}\, \sigma_\lambda\, (dV_g/df)}. \tag{8}$$

These relationships describe the trade-off between bandwidth and distance. When the required filter bandwidth W, according to equation (7), is much less than the spectral emission width of the LED $2\sigma_\lambda$, the product BL increases by $2\sigma_\lambda/W$, according to equation (6).

3. Numerical results

A practical fibre-optic link utilizing an LED, a low-loss multi-mode fibre [12], and a Si APD receiver is considered:

$$\lambda_0 = 0{\cdot}85\ \mu\mathrm{m}, \quad 2\sigma_\lambda = 330\ \text{Å},$$
$$n = 1{\cdot}45, \quad dV_g/df = 10^{-8}\ \mathrm{m/cycle},$$
$$T_0 = 0{\cdot}7, \quad \eta = 0{\cdot}7, \quad G = 100,$$

and SNR = 20 dB, corresponding to a bit error rate of 2×10^{-7} [9].

Equations (7) and (8) simplify to

$$W^2L = 5\times10^4 \exp(\alpha L)/P_0 \quad [\text{Å}^2\,\mathrm{km}] \tag{9}$$

and

$$B^2L = 5\times10^4 P_0 \exp(-\alpha L) \quad [(\mathrm{Mb/s})^2\,\mathrm{km}], \tag{10}$$

where P_0 is in microwatts. Two values of P_0 of 100 and 400 μW and fibre losses of 4·3 and 8·6 dB/km are considered, corresponding to $\alpha = 1$ and 2 neper/km respectively.

Figure 3 shows the optimum filter bandwidth to achieve maximum information pulse rate.

Figure 4 shows the effect of filtering in increased system capabilities. Without filtering, dispersion would limit the information pulse rate to 150 Mb/s for a 1 km length. Considering a fibre with loss of 8·6 dB/km, the maximum pulse rate would increase to 800 Mb/s, when a 60 Å filter is used for $P_0 = 100\ \mu$W. For $P_0 = 400\ \mu$W, the maximum pulse rate doubles to 1·6 Gb/s when using 30 Å filter.

Figure 5 illustrates the importance of proper choice of the filter bandwidth. If a 30 or 120 Å filter is used instead of the optimum 60 Å filter, for a 1 km fibre of

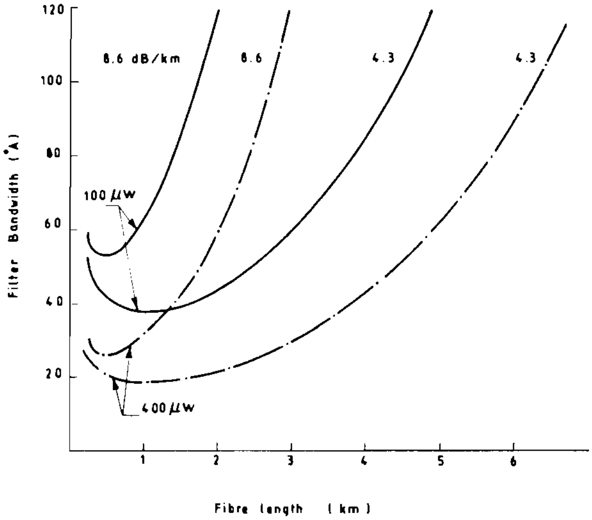

Figure 3. The optimum filter bandwidth to achieve maximum information pulse rate ($\lambda = 0{\cdot}85\,\mu$m).

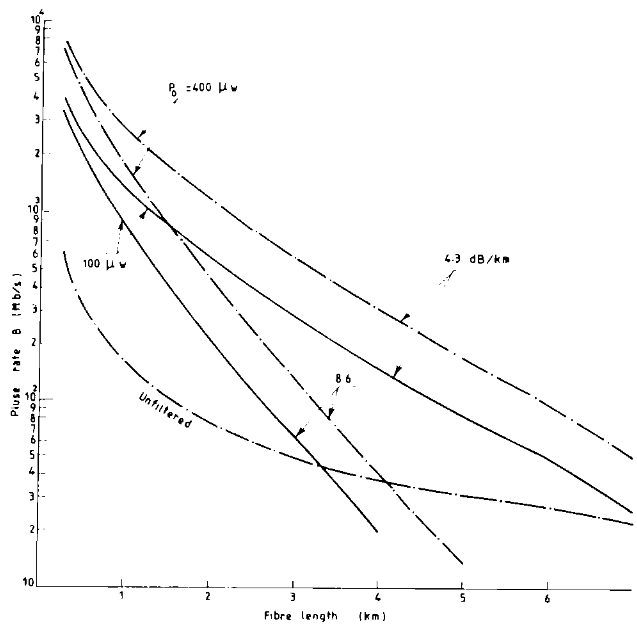

Figure 4. The dependence of information pulse rate on fibre length (filters are selected according to figure 3.)

8·68 dB/km loss when $P_0 = 100\,\mu$W, the maximum pulse rate should not exceed 400 Mb/s.

For LEDs operating at wavelengths other than 0·85 μm, figure 6 shows that the optimum filter bandwidth increases almost linearly with wavelength, whereas the corresponding maximum pulse rate increases substantially, even when neglecting the wavelength dependence of the fibre loss.

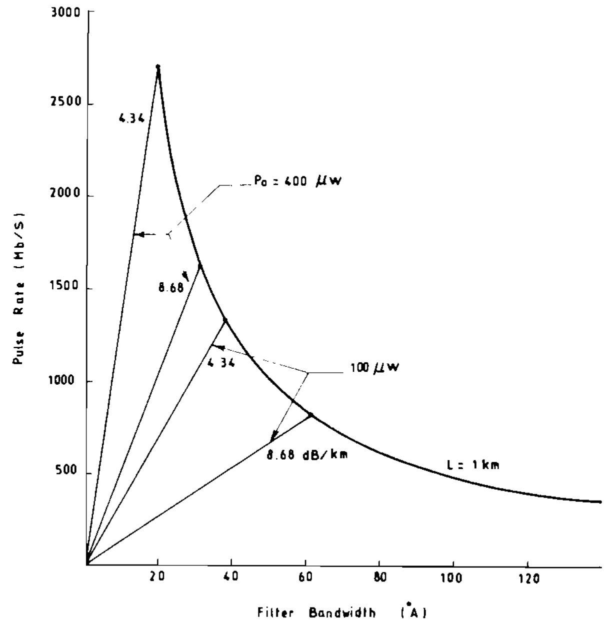

Figure 5. The dependence of the maximum information pulse rate on the filter bandwidth. $L = 1$ km.

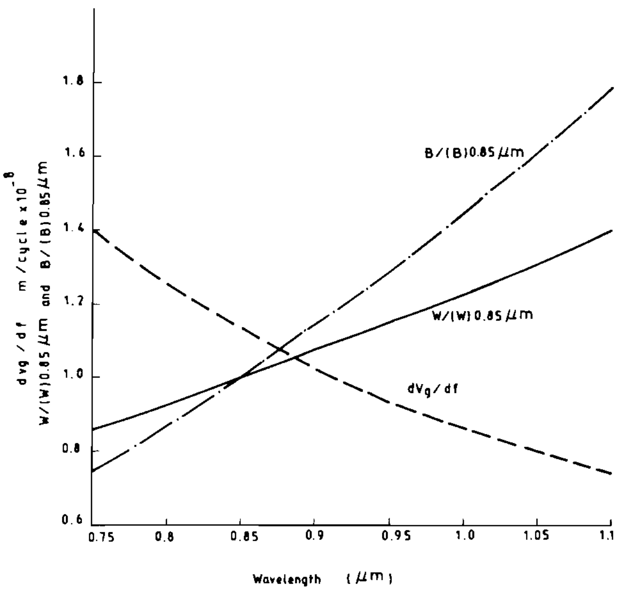

Figure 6. The dependence of the optimum filter bandwidth and the corresponding maximum information pulse rate on the central wavelength λ_0 of the LED.

The penalty paid for these improvements is the reduction of the received power by the factor $T_0 W \sqrt{(2\pi)} \sigma_\lambda$. The power reduction penalty would range from 10 to 16 dB according to the filter bandwidth, as shown in figure 7.

This work aims to give a useful practical guide to the proper choice of spectral filter bandwidth. The numerical results obtained suggest that this technique can be very useful for short-haul digital links.

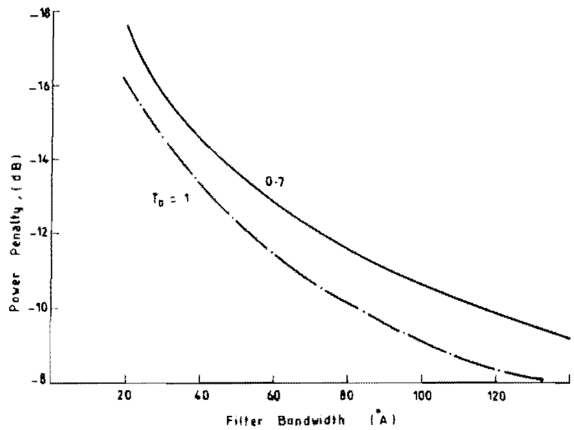

Figure 7. The dependence of the power reduction penalty on the filter bandwidth.

En choisissant convenablement le filtre spectral à utiliser avec une ligne de communication digitale à fibre optique et diode électroluminescente, on peut obtenir un accroissement substantiel du débit d'information, lorsque le système est limité en bande passante par la dispersion du matériau. La bande passante optimale dépend de la longueur de la fibre, de l'atténuation, de la dispersion et de la puissance optique de la diode électroluminescente.

Un filtre de 60 Å augmentrait le débit maximal de 150 Mb/s à 800 Mb/s pour une fibre d'un km de longueur, avec une atténuation de 8,6 dB/km et une puissance optique de 100 μW. Il en résulte une réduction de puissance d'environ 13 dB.

Durch geeignete Wahl des in einer digitalen faseroptischen LED-Nachrichtenverbindung eingesetzten Spektralfilters läßt sich eine wesentliche Erhöhung der Informationspulsrate erreichen, falls das System wegen der Materialdispersion bandbegrenzt ist. Die optimale Filterbandbreite hängt ab von der Faserlänge, der Dämpfung, der Dispersion und der LED-Ausgangsleistung.

Ein 60 A-Filter erhöht die maximale Impulsrate bei 1 km Faserläng mit 8,6 dB/km Dämpfung und 100 μW eingekoppelter optischer Leistung von 150 Mb/s auf 800 Mb/s. Es ergibt sich ein Leistungsverlust von etwa 13 dB.

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