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Creating parallel independent communication channels in multimode fibre networks by mode group division multiplexing

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Mode group diversity multiplexing enables to carry a number of signals independently in a multimode fibre network, by deploying separate mode groups in parallel. Its functionality is similar to wavelength multiplexing, but relatively expensive wavelength-selective devices are not needed; these can be replaced by lower-cost parallel non-wavelength-specific devices and electronic signal processing circuitry. Well-chosen selective launching of the mode groups is needed, and for this both theoretical and experimental investigations have been carried out. First results show that multiplexing of about four different signal streams is feasible, providing the foundation for a low-cost service-integrated in-house optical network.

1 Introduction

Multimode fibre is an attractive medium for broadband in-house networks, being easier to install than single-mode fibre due to its large core diameter. It is already widely accepted for short-range data communications in broadband LANs, benefiting from low-cost multimode fibre transceiver modules. Moreover, multimode Polymer Optical Fibre (POF) offers large flexibility and ductility, which further reduces installation costs in often less accessible customer locations [1]. Its attenuation per unit length is being reduced steadily, as production technology improves; presently, losses below 10 dB/km have been obtained. The bandwidth figures are also being improved, by means of better control of the graded refractive index profile. Bandwidth-times-length products have reached some 1 to 5 GHz·km, which however is and will remain much lower than those of single-mode fibre networks. This limited bandwidth obstructs the desired integration of multiple broadband services into a single in-house fibre network. Therefore new methods are being investigated to overcome the bandwidth limitation. This paper reports on a technique which we have termed *Mode group diversity multiplexing (MGDM)*, for realising a number of independent parallel communication channels by deploying subsets of the many guided modes in multimode fibre. By means of the MGDM technique, different categories of broadband services for wireless as well as wired user terminals could be integrated in a single POF in-home network, where the multiplexing of the services can be done in a centralised site such as the residential gateway which connects to the various outdoor access networks.

2 Mode group diversity multiplexing

The modal dispersion resulting from the different propagation times of the modes guided in a multimode fibre (MMF) is the main cause of its limited bandwidth. However, one may get benefits from launching not all the guided modes simultaneously. Firstly, with restricted launching of just a subset of the modes, the bandwidth is increased due to the reduced propagation time differences. Secondly, one may launch different signals into different mode groups, thus creating parallel transmission channels. This novel method, which we have termed mode group diversity multiplexing, is illustrated in Fig. 1 [2].

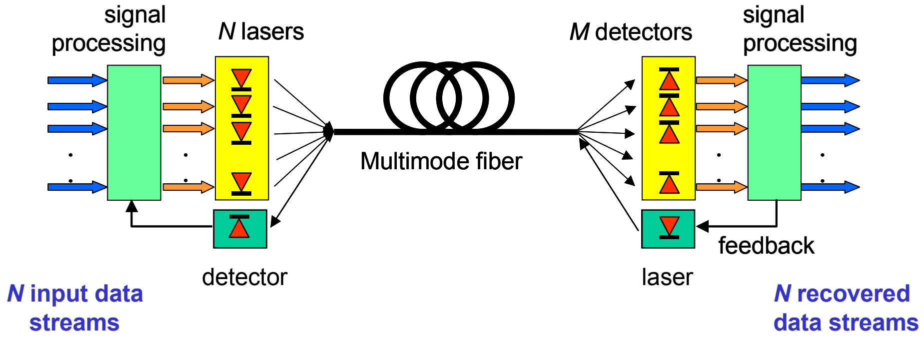

Fig. 1 Mode group diversity multiplexing

The concept is based on using a number *N* of independent optical transmitters at one end of the system, and *M* receivers at the other end. Each transmitter launches a data signal into a different group of modes. Each spatially selective receiver detects a mixture of the *N* signals, and in a subsequent electrical signal processor the mixtures are unravelled in order to produce the N signals separately again. For this, the signal processor needs to invert the transmission matrix which describes the signal transfer from the N transmitters to the M receivers. The coefficients of this transmission matrix may be determined by initialising the system through sending some training sequences known by the receiving site. The fluctuating mode mixing conditions in the multimode fibre will cause variations in the transmission matrix coefficients. Assuming that these fluctuations are much slower than the bit rates of the signals, strategies to adapt the coefficients dynamically may be devised. E.g., the fluctuations may be monitored by adding some redundancy to the transmitted signals by means of line coding in a signal processing stage at the transmitter site, which enables the detection of transmission errors at the receiver site. A feedback channel may instruct the transmitter site to optimise the mode group launching conditions, and to restart the initialising training period in case of loss of the adaptation process.

3 Launching different mode groups

An analysis has been made how mode groups can be excited separately, and how thus different near-field patterns (NFPs) of light intensity can be generated at the output of the fibre link. The propagation of light rays in multimode fibre can geometrically be described using the eikonal equation [3]; a light ray congruence solution is characterized by the parameters *h* and *k* given by

$$k = n(r)\cdot\cos\theta(r) \quad \text{and} \quad h = n(r)\cdot\frac{r}{a}\cdot\sin\theta(r)\cdot\sin\psi(r)$$

where $n(r)$ is the local refractive index as a function of the radial coordinate r, θ is the angle of the ray with the z-axis of the fibre, and ψ is the azimuth of the ray; see Fig. 2.
It can be shown that at the fibre output annular NFPs are generated; for a parabolic refractive index profile, the inner radius r_0 and outer radius r_1 of the annular NFP can be calculated to be

$$r_0/a = \frac{1}{NA\sqrt{2}}\left\{n_0^{\,2} - k^2 - \sqrt{\left(n_0^{\,2}-k^2\right)^2 - \left(2\,h\,NA\right)^2}\right\}^{1/2}$$

$$r_1/a = \frac{1}{NA\sqrt{2}}\left\{n_0^{\,2} - k^2 + \sqrt{\left(n_0^{\,2}-k^2\right)^2 - \left(2\,h\,NA\right)^2}\right\}^{1/2}$$

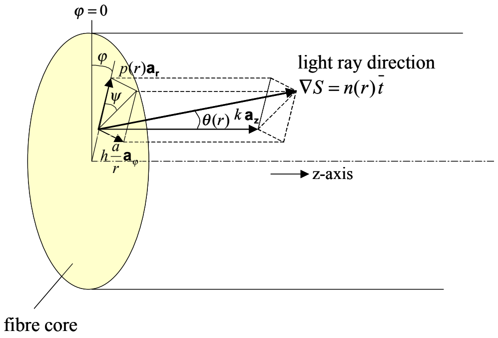

Fig. 2 Ray propagation in a multimode fibre

where *NA* is the theoretical numerical aperture of the fibre, *a* is the core radius, and $n_0=n(0)$. For meridional rays crossing the fibre axis, h=0 and thus r_0=0 meaning that the NFP radially extends from the core centre to an outer radius r_1 depending on k. Non-meridional rays follow a helix-shaped path, confined between two caustic cylindrical planes centred around the fibre's axis, with radius r_0 and r_1 , respectively. The normalised radial light intensity distribution (normalised on the total light power between the two caustic planes) for a (h,k) light ray congruence can be derived to be

$$\Phi_{nr}(r,h,k) = \frac{1}{2\pi\, r \cdot v_r(r) \cdot \tau_s(h,k)} = \frac{n^2(r)}{2\pi\ c_0\, r \cdot p(r) \cdot \tau_s(h,k)}$$

where for a parabolic graded-index distribution

$$p(r) = \frac{NA}{a\,r}\sqrt{(r^2 - r_0^2)(r_1^2 - r^2)} \quad \text{and} \quad \tau_s(h,k) = \frac{\pi}{4\,c_0} \cdot \frac{a}{NA} \cdot \left(n_0^2 + k^2\right)$$

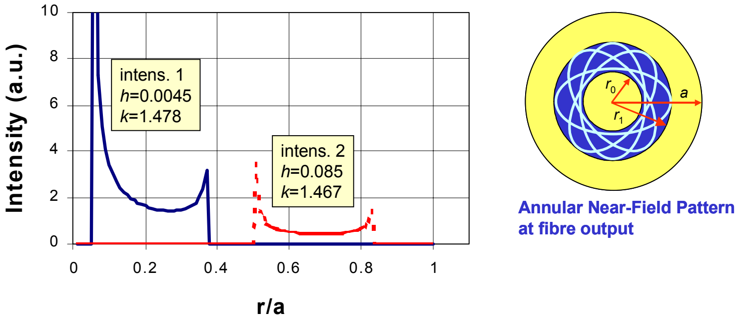

Fig. 3 Radial distribution of NFP for non-meridional rays, for different launching condition parameters (*h, k*) ; *NA*=0.2, n_0=1.48

The radial intensity distribution of the NFP of a non-meridional ray is exemplified in Fig. 3 . By controlling the light ray launching conditions (h,k), the shape of the annular NFP can be adjusted.

4 Experimental results

Measurements with restricted mode launching have been made of the NFPs of a 100 metres PMMA graded index POF; see Fig. 4. These results confirm the annular shape of the NFPs. There is some central overlap in the intensity patterns due to the meridional rays in the mode groups, which will generate non-zero terms outside the diagonal of the system's transmission matrix. However, the NFPs in Fig. 4 b) and c) show sufficient complementarity in order to support different communication channels after elimination of this crosstalk by the matrix inversion in the signal processing circuit at the receiver site.

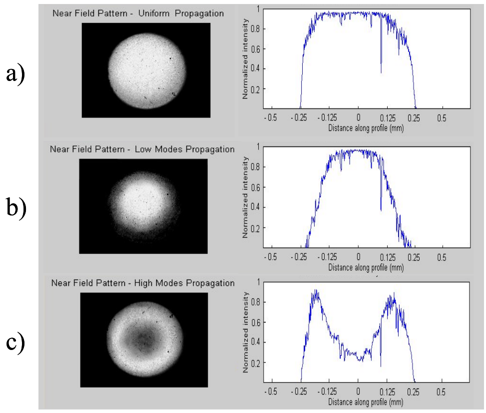

Fig. 4 NFP at output of 100 metres PMMA GI-POF
a) exciting all modes; b) exciting low-order modes (high *k*) only; c) exciting high-order modes (low *k*) only

Knowing the transmission matrix coefficients, these may also be used for selective mode group transmission in the upstream direction, thus enabling bi-directional communication.

Fig. 5 illustrates which functionalities may be needed at the transmitter and the receiver sites of an MGDM system.

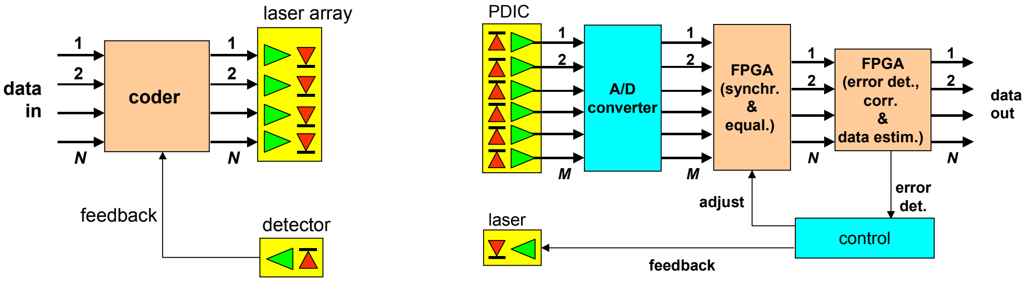

Fig. 5 Transmitter and receiver sites

5 Conclusions

The mode group diversity multiplexing system functionality is basically similar as wavelength division multiplexing, but without using (costly) wavelength-specific sources and wavelength (de-)multiplexer modules. Instead, electronic signal processing is needed to separate the various channels, and an array of laser diodes and of detectors. Provided that low-cost electrical integrated circuits and integrated optical sources (e.g. VCSEL array) and detectors can be used, MGDM may thus be an economically attractive alternative for WDM in short-range integrated-services networks.

6 Acknowledgement

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7 References

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