Review Article: Space-Division Multiplexing in optical Fiber

For years optical fibers have been used as a method for data communication and has been rapidly advancing. Current optical fiber can reach a maximum speed of 940 megabits per second with extreme low lag time as information travels in the wave guide at almost the speed of light. Yet, the amount of data which can be transmitted without cross talk has reached a bottleneck, so spacial multiplexing is suggested in the article. However, numbers of work still needs to be done.

1. INTRODUCTION

The author of the article [1] suggested the concept of spacial-division multiplexing (SDM) in a single wire, and that such concept existed since 1979 but was never fulling implemented. As need for data rate increases, the transmission process without cross talk has reached an end. The author's suggestion in the article is unnecessarily complicated for a simple problem, and each with its own flaws that would introduce new issues for a mature design in optical waveguide.

By modulating time, wavelength, polarization and phase has reached a bottleneck. Single-Mode fiber cannot carry more than about 100 T-bits/s of data. Which is why space division multiplexing is being developed.

2. TYPICAL MULTIPLEXING AND MODULATION METHODS

Data is appended onto a carrying wave though these modulation. Multiplexing can be done accordingly.

A. Modulations

In Phase Modulation, the function $\phi_\varepsilon(t)$ carries the encoded information, and it varies the phase of the wave.

$$E(0,t) = \hat{e}|\varepsilon|e^{i\phi_\varepsilon(t) - i\omega t}$$

In Frequency Modulation, $\omega(t)$ varies with time and contains the information.

$$E(0,t) = \hat{e}|\varepsilon|e^{i\phi_\varepsilon - i\omega(t)t}$$

In polarization Modulation, polarization varies with the signal.

$$E(0,t) = \hat{e(t)}|\varepsilon|e^{i\phi_\varepsilon - i\omega(t)t}$$

The amplitude of the carrier wave carries the information

$$E(0,t) = \hat{e}|\varepsilon(t)|e^{i\phi_\varepsilon - i\omega t}$$

B. Multiplexing

C. TDMA (Time Division Multiplexing)

Each client has its own time slot, and can only send information at their own time slot.

D. FDMA (Frequency Division Multiplexing)

Each client has its own frequency slot, information were sent with different frequency.

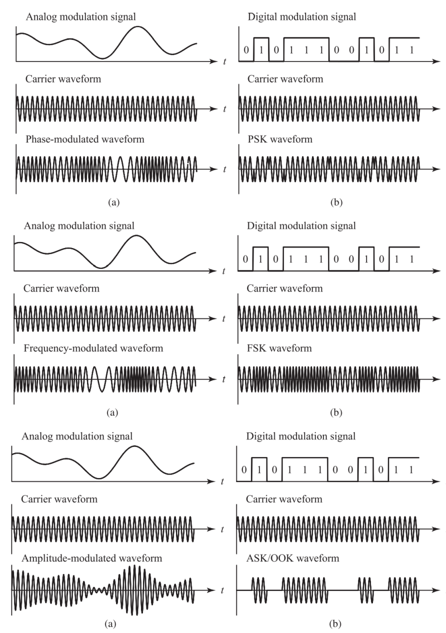

Figure 1. Phase(Top), Frequency(Middle), and Amplitude(Bottom) modulations. From textbook[2]

3. APPROACHES FOR SPACE-DIVISON MULTIPLEXING

A. Multicore fibres

As suggested in the article, in Multicore fibres, the paths are defined by physically aligning an array of single-mode cores with sufficient gaps between them to prevent cross talks. Variations in materials would be required, and generally for achieving a cross talk level of -25 dB to avoid transmission penalties.

However, in order to maintain the distance between the wave guides, another medium is required to hold them apart. This medium would need to be carefully selected in order to avoid substrate radiation and substrate-cover radiation modes. These modes could easily happen which could easily happen under certain condition base on the flexibility and usage of the fibers, leaks some of the light beams into another medium, introducing cross talk and attenuation. Bending of wave-guide commonly occurs as situation in real life varies and could cause the light's incident angle changes to larger than the critical angle of both side of the medium, so total internal reflection no longer occurs.

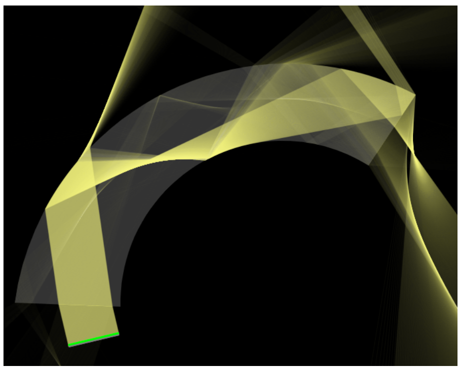

Figure 1. Image of simulating leakage over curves. Curving a cable is common when installing fiber obtic cable, this would not normally be a large issue, however when multiple cores are in the same cable, this introduces cross talk.

More over, codirectional coupling as the lights are traveling in the same direction could occur leading to an increase in cross talk not only when they are leaked into the same medium but also in two parallel wave guides. Hence an increased in distance is required. This is also mentioned in the article as a method to reduce cross talk. However as they pointed out: fiber optic cables over the diameter of 200 μm is susceptible to fracture and renders them inpractical. Having multiple axial is also reducing flexibility of the wave-guide making them more difficult to maneuver.

It is also suggested that mode coupling may be beneficial when the wave guides are closer together to enhance linear mode coupling, establishing super modes. This approach combines multi-core approach into multi-mode approach, which has its own problems as will be discussed below.

B. Multimodes fibres

In such case the signals are seperated into different modes than transmitted within the same wave-guide which means that they have significant spatial overlap leading to random coupling between modes during propagation. When light is coupled from one mode to another during the transmission cross talk will happen. Common modes are HE_{11}, TM_{01}, TE_{01}, HE_{21}, and LP modes.

This could led to another problem as sharing the same wave-guide creates difficulties in digital signal processing(DSP). DSP systems would now need to consider the polarization to separate the signal within the same wave-guide and be built with multi-input-multi-output (MIMO) in mind. For example, it is common for waveguides to support both TE_0 and TM_0 and not TE_1 and TM_1 at the same time making the choice of modes difficult as shown in example 3.15 of the book Principles of Photonics[2]. Further more, mode coupling often occurs especially easily when they are traveling in the same wave-guide. That will requires people to work on more more complex modal basis sets in order to reduce mode coupling [1].

Not only could coupling cause cross talk, but it can also cause interference and distort data. The receiver would also be more difficult to implement as mode coupling is inevitable and they have a significant spatial overlap. Since coupling is inevitable it is also suggested that strong codirectional coupling be utilized as part of the solution to reduce the amount of multi-input-mupti-output(MIMO) required for the DSP system. This is significantly more difficult for increasing the data rate yet not the reliability. According the the article a seven-core multi-mode MCF can only maintain its rate within 100 m of range.

4. TECHNOLOGY AND INTEGRATION

As mentioned in previous section, one of the main problem involved is the system in general and the signal processing system. The upgrade from single wire to SDM can be a rebuilt of current system or making it downward-compatible. Merely reducing cross-talk without scalability brings no benefit over current design. The implementation of amplifier for the signal is also unclear, which means that the accuracy of the receiver must be a lot higher than traditional ones. More research on gain medium is required to achieve a high efficiency and low differential gain for many modes.

5. CONCLUSION

Although space division multiplexing is promising, there are still many problems that needs to over come.

REFERENCES

1. D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," Nat. Photonics **7**, 354–362 (2013).
2. J.-M. Liu, *Principles of Photonics* (Cambridge University Press, 2017).