Dr. H. Paul Shuch, *N6TX*
Professor of Electronics
Pennsylvania College of Technology
One College Avenue
Williamsport, Pennsylvania 17701

WAVELENGTH DIVISION MULTIPLEXING

Without fuss or filters

Just as RF multiplexers generally employ LC filters, and microwave multiplexers usually include cavities, fiber optic multiplexers have traditionally used simple optical filters to combine and separate signals. My students and I have been exploring an alternative technique that involves combining sound engineering practice with good old ham ingenuity. The result promises to simplify equipment, increase reliability, and improve both spectral and power efficiency.

Introduction

Ever since Claude Shannon[1] first quantified the relationship between bandwidth and information content, communications engineers have been vying to develop the most spectrally efficient modulation scheme. Most contenders have incorporated some form of multiplexing, where multiple communications channels share a common RF, microwave, or optical link.

Time division multiplexing samples a number of different information channels sequentially for transmission on a single carrier. Frequency division multiplexing generally involves summing a multitude of independent subcarrier frequencies, each with its retinue of modulation sidebands. In polarization division multiplexing, two different information signals are modulated onto carriers of the same frequency, which are propagated with their elec-

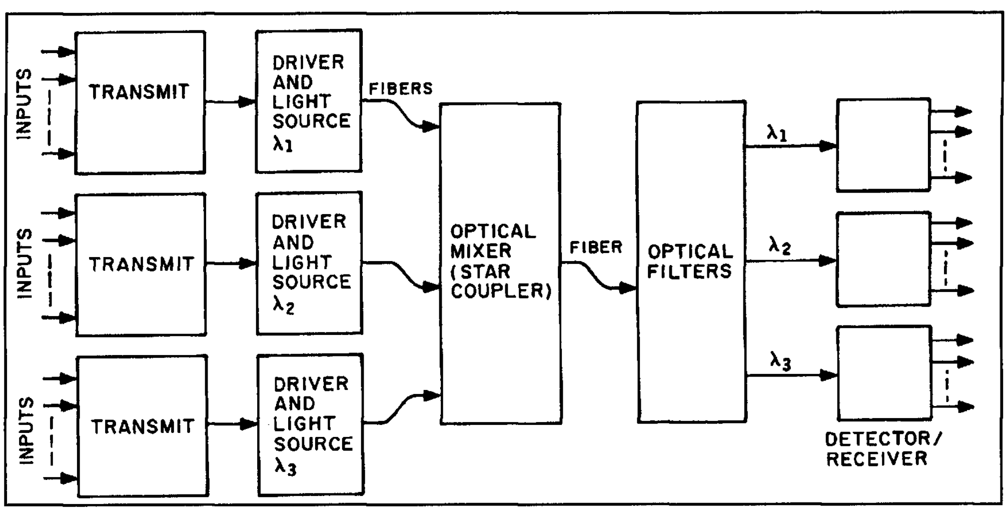

Figure 1. Typical wavelength division multiplexing scheme.

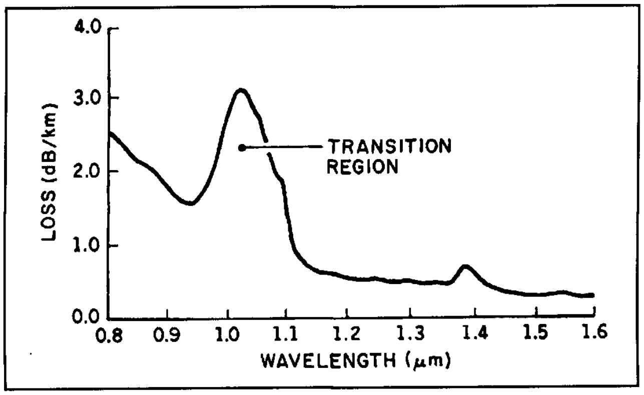

Figure 2. Attenuation versus wavelength for typical single-mode glass fiber.

trostatic fields oriented orthogonally. Wavelength division multiplexing incorporates independently modulated carriers of different frequencies sharing a common transmission medium. It is this latter technique to which the present study directs itself.

Prior art

Figure 1 from **Reference 2** depicts a traditional fiber optic wavelength division multiplexing scheme. Three infrared sources (lasers or light emitting diodes—LEDs) of different wavelengths are modulated independently with their respective channel intelligence. Although any number of optical carrier frequencies might be used, common practice is to generate carriers at wavelengths typically near 850, 1300, and 1550 nm. As you can see in **Figure 2**,[3] these wavelengths represent low loss windows for typical single-mode glass fiber.

Optical star couplers combine the three modulated carriers onto a single glass or plastic light pipe. At the receive end of the fiber, couplers split the output beam into three identical components, each containing elements of all three signals. Bandpass filters at the coupler outputs let each of three photodetectors "see" and respond to a single carrier frequency. Demultiplexing could be achieved as readily using wavelength selective couplers. In fact,

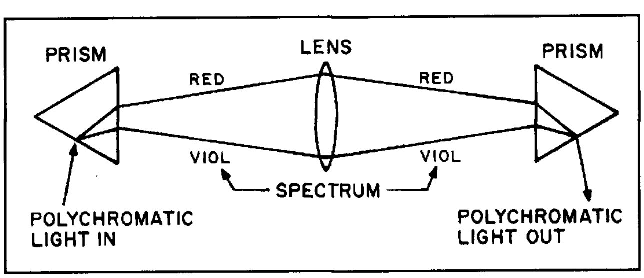

Figure 3. Prisms can both combine and separate spectral components.

Hecht[4] indicates that the "major use of wavelength-selective couplers is in WDM."

The system just described, though effective, suffers from a number of drawbacks. The bandpass characteristics of the individual filters or wavelength selective couplers limit the modulation bandwidth, hence data rate, of the three channels. A filter narrow enough to reject the adjacent channels is likely to exhibit considerable insertion loss at the intended passband wavelength. Additionally, any three-way signal splitter will, even neglecting dispersion and reflective losses, attenuate the desired signal by at least 5 dB. For that matter, the coupler used to combine the signals at the transmit end will similarly contribute to system losses. Consequently, the recovered optical amplitude will, for each channel, be at least an order of magnitude below what might have been accomplished over the same fiber, under single channel conditions.

Palais[5] notes that "wavelength division multiplexer designs can be based upon either of two mechanisms: angular dispersion or optic filtering." He acknowledges the limitations of filter-type multiplexers, as noted, and then identifies two devices for achieving angular dispersion—the prism and the blazed reflection grating. He presents an application example using a combination of a GRaded INdex (GRIN) rod lens and a reflective diffraction grating, but leaves implementation of a prism multiplexer to the imagination of the reader. The present project represents an attempt to reduce to practice a multiplexer using prisms to achieve angular dispersion.

The proposed solution

The ability of a triangular dispersing prism to separate polychromatic light into its constituent spectral components has been well known for three centuries, and was well documented by Newton. Dating from the same period, application of Huygens' Principle[6] tells that such a prism should also be able to combine monochromatic light sources into a polychromatic beam (see **Figure 3**). Beam splitters are one such application of prisms. Hecht[4] states that "many optical systems use devices called beam splitters to separate (sic) light of different wavelengths into a single beam." Why not apply prisms to the task of combining and separating modulated carriers of diverse wavelengths, eliminating the signal couplers and filters shown in **Figure 1**, and with them, their attendant limitations?

The solution proposed to my Fiber Optic Principles class at the Pennsylvania College of Technology in April 1992 is depicted in **Figure 4**. Here three modulated light sources (laser diodes or LEDs) producing carriers of differing wavelengths are mounted on one face of a triangular prism, with spacing selected so a single polychromatic beam emerges. Said beam is in turn coupled into a glass fiber (a lens will doubtless be required to launch the resulting beam within the acceptance cone of the fiber). At the receive end of the fiber (where again a lens may be used to couple between fiber and prism), a second prism separates the wavelength multiplexed signal into its constituent parts, with a separate photodetector mounted at each of three appropriate spots on the prism's output face. As a result, wavelength division multiplexing and demultiplexing can be achieved without the use of couplers, filters, or their attendant loss.

The next step is to determine in the laboratory whether such a scheme can actually be reduced to practice.

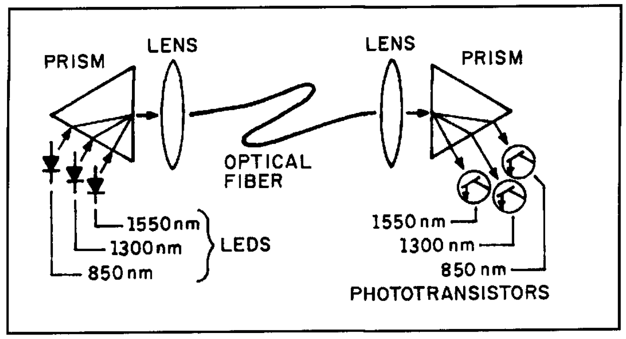

Figure 4. Use of prisms for wavelength division multiplexing.

Reduction to practice

Although the intended application will likely involve the use of infrared carriers, prototyping the system with visible sources facilitates direct observation of the system's optical properties. Initial implementation of the proposed wavelength division multiplexing scheme was attempted with red, green, and blue coherent sources. (It is little coincidence that the television primary colors were selected for initial analysis.) The red source used was a small Helium-Neon laser, operating at its familiar 632.8 nm primary visible transition. For blue light, a 488 nm Argon Ion laser was chosen. A tunable Helium-Neon laser provided a green output at 543 nm.

Initial attempts to converge the three sources into white light through a dispersive 60-degree glass prism have been unsuccessful, due to the critical angular and lateral alignment required of the three laser sources. It turned out to be far easier to combine the three carriers in a beam splitter constructed from four 45-degree reflective glass prisms, as shown in **Figure 5**. Despite relatively high combining losses, a bright white beam emerged. By blocking combinations of laser beams, it was possible to crudely approximate the RGB Television secondary colors (yellow, magenta, cyan). A more precise rendering of secondary colors would require carefully balancing the amplitudes of the three primary sources.

In the demonstration system, polychromatic light emerging from the beam splitter was focused into a 10-meter length of 125-micron diameter multi-mode step index glass fiber, the ends of which were well cleaved and polished. A beam expander collimated the fiber's output, focusing it into a 60-degree dispersive glass prism. Three spatially distinct primary colors were clearly projected from the prism's output face. No attempt was made to modulate the three carriers, or to couple light from the prism into three independent photodetectors. Nevertheless, I feel this breadboard system has

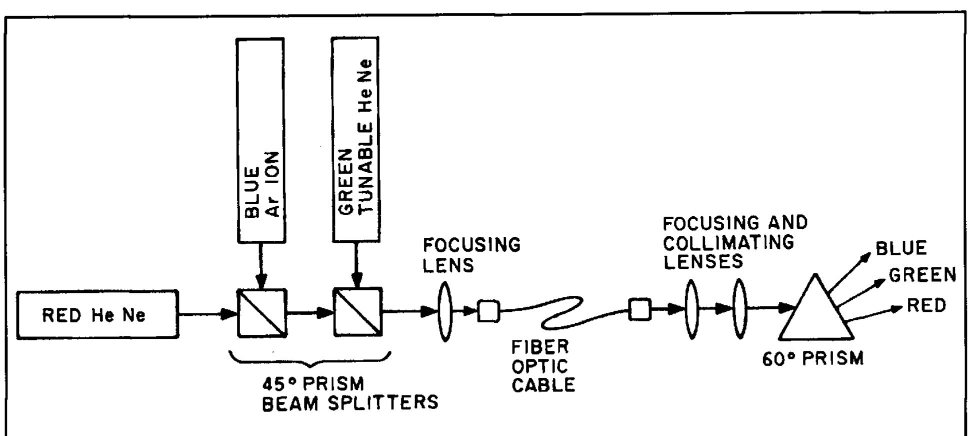

Figure 5. Prototype system demonstrated in the laboratory at the Pennsylvania College of Technology.

demonstrated the key features of wavelength division multiplexing.

Implications for further study

The use of a dispersive prism for combining three laser sources into a monochromatic beam remains to be demonstrated. As was mentioned, the position of the three laser beams is critical. The beam splitters demonstrated are workable, but highly inefficient. It is important to solve the alignment problem if the system is to achieve its potential for power efficiency.

It's not clear how best to position photodetectors to recover the individual carriers efficiently. Mounting the detectors directly on a prism face is appealing in its simplicity, but again, physical positioning is highly critical. Once these problems have been addressed, the next logical step will be to modulate the individual sources and measure system risetime. This will allow for the quantification of the overall bandwidth limitations.

About the institution

The Pennsylvania College of Technology is a subsidiary of the Pennsylvania State University, offering undergraduate technical training in 79 different specialties, including lasers, fibers optics, and electronic communications. Associate degree and, more recently, Baccalaureate studies feature relatively small classes, with emphasis on practical hands-on experience. The investigation just described is typical of the kinds of projects in which our students are involved. Inquiries from students and industry are always welcome.

Acknowledgments

I am indebted to the Spring 1992 Fiber Optic Principles class at the Pennsylvania College of Technology for acting as a sounding board for their Professor's ruminations on the concepts presented here. Three of my students in particular—Brett Shelton, Dennis Grace, and Brad Hilbish—showed great initiative in prototyping the proposed system. Thanks are also due to an enlightened colleague, laser instructor Karl Markowicz, for bringing some coherence to our analysis.

This manuscript first appeared in *Proceedings of Microwave Update 1992*, published in October 1992 by the American Radio Relay League, Newington, Connecticut. It is reprinted here with their kind permission.

REFERENCES

1. C.E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, (27): pages 379 and 623, 1948.
2. H. Zanger and Cynthia Zanger, *Fiber Optics—Communications and Other Applications*, Macmillan, New York, 1991, page 116.
3. D.J. Sterling, *Technician's Guide to Fiber Optics*, Delmar, New York, 1987, page 63.
4. J. Hecht, *Understanding Fiber Optics*, Sams, Indianapolis, 1987, page 196.
5. J.C. Palais, *Fiber Optic Communications*, Prentice Hall, Englewood Cliffs, New Jersey, 1992, pages 230–233.
6. F.A. Jenkins and Harvey E. White, *Fundamentals of Physical Optics*, McGraw-Hill, New York, 1937, pages 52–53.