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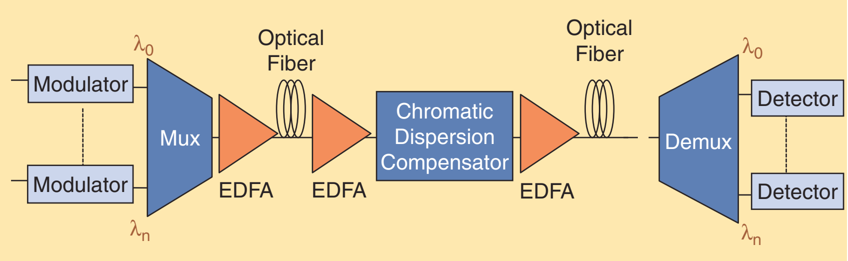
Signal Processing for Optical Communication

Optical communication has played a significant although hidden role in our everyday life as the backbone of communication networks. This is a field that seems to appeal to those researchers and engineers with an interest in the physical aspects of optical communications. Thus, optical communication devices are often modeled and designed from physicists' point of view. With the increased demand for advanced optical communication systems, the technical specifications for optical devices such as optical filters are stricter than ever. The numerous technical challenges that accompany the needed high transmission rate optical systems require novel solutions. In recent years, researchers in optics have come to the realization that signal processing theory can help to provide these novel solutions in optical communication device and system design. As an enabling technology, signal processing can provide great insight into the working principles of optical communication devices and can thus bring about novel solutions to some important optical communication issues.

In this article, three interesting examples are presented to illustrate the application of signal processing techniques to the design of state-of-the-art optical communication devices. These examples are an optical wavelength interleaver, an all-pass filter for chromatic dispersion compensation, and an electronic equalizer. Researchers and engineers with a signal processing background may be pleased to learn how signal processing techniques can be used to design cutting-edge optical communication devices. These examples illustrate how interdisciplinary cooperation among various research fields can facilitate technology progress. The wavelength division multiplexing (WDM) system, which is the dominating optical communication system, will be introduced in the next section. Three signal processing application examples for optical communications will then be presented in the subsequent sections.

WDM SYSTEM

Since its development in the 1990s, the WDM system has emerged as the method of preference for the development of optical communication systems. The primary difference between a WDM system and a traditional optical communication system is that the WDM system transmits multiple channels over a single fiber, whereas the traditional optical communication system only transmits one channel over a single fiber. To increase optical network capacity, system designers using WDM are able to squeeze multiple channels into a given bandwidth. When channel frequency spacing is dense, say 100 GHz, the WDM system is referred as the dense WDM (DWDM) system.



[FIG1] A simplified WDM system diagram.

A simplified WDM system diagram is illustrated in Figure 1. For each channel, an optical modulator is used to convert electrical signals to optical signals. At the transmitter side, a wavelength multiplexer is used to combine multiple optical channels together so that they can be transmitted over a single fiber. The erbium-doped fiber amplifier (EDFA) amplifies an optical signal directly to compensate signal power loss caused by optical fibers. It is the use of an EDFA that makes the WDM system possible. Before the invention of EDFA, there was no way to amplify an optical signal directly in an economical way. After being transmitted over certain distance, a repeater was needed to convert optical signals to electrical signals and then to regenerate an optical signal to guarantee signal quality. This optical/electrical (O/E)/optical conversion made multichannel transmission over a single fiber infeasible economically since channels at different wavelengths have to be separated before O/E conversion to be regenerated individually, and then they must be grouped together again. Fortunately, this scenario has been improved by the use of EDFA since multiple optical channels can be simultaneously amplified through EDFA. This EDFA technique can be used to boost optical signal before transmission, compensate optical signal power loss during transmission, and preamplify signal power at the receiver. It is also worthy of note that since the invention of EDFA, other types of fiber amplifiers and solid-state amplifiers also have been developed to amplify optical signal directly.

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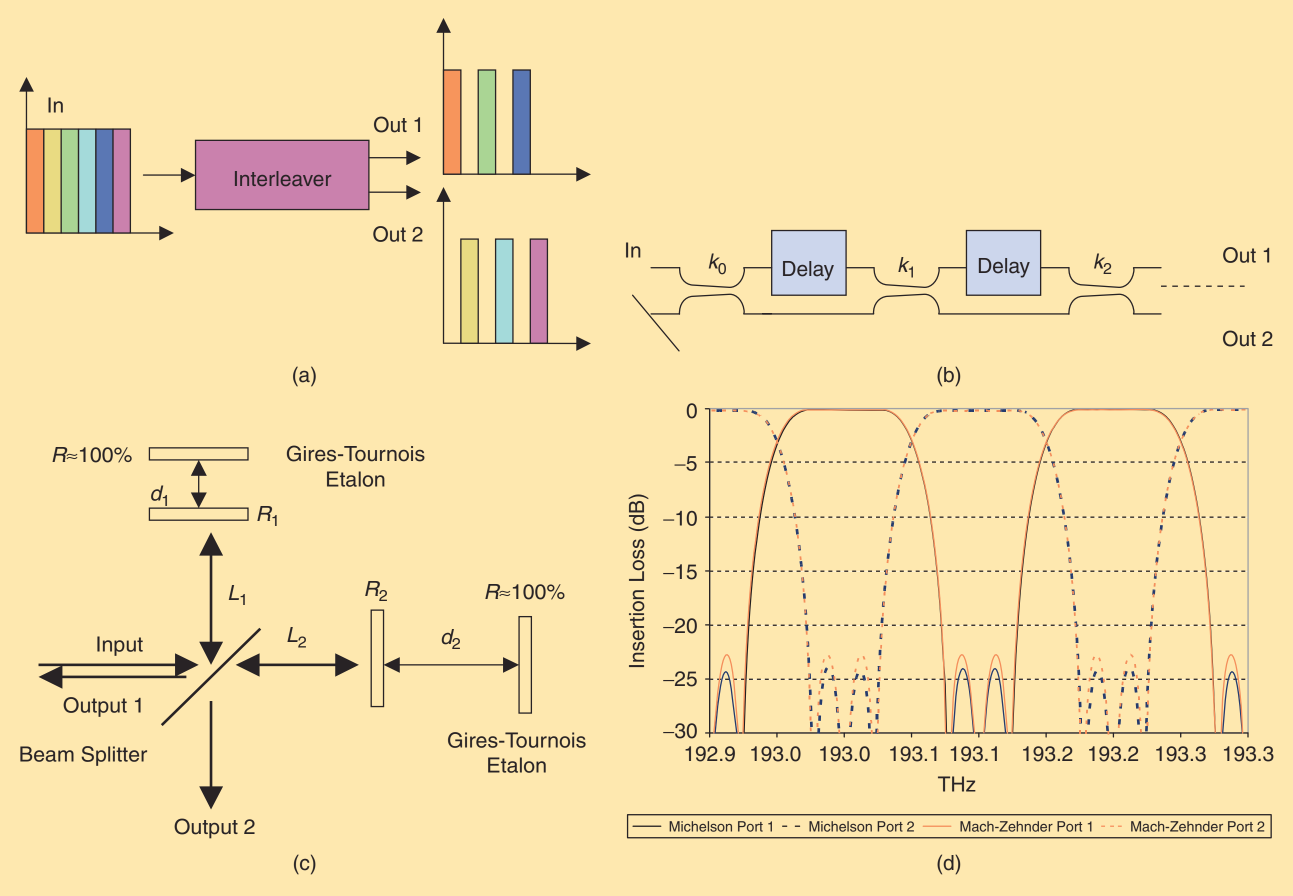
Besides optical fiber insertion loss, which attenuates optical signal power, optical fiber has chromatic dispersion that distorts signal phase. To compensate chromatic dispersion, a dispersion compensator such as a dispersion compensation fiber or all-pass filter is used (this all-pass filter will be described later). A chromatic dispersion compensator must be installed between optical fiber transmission segments (usually around 80 km long) in an optical link to guarantee signal quality. Typically, an amplifier, as illustrated in Figure 1, is used to compensate signal power attenuation caused by the dispersion compensator. With the use of an EDFA to compensate optical signal attenuation and the dispersion compensator to compensate fiber dispersion for each transmission segment as illustrated in Figure 1, an optical signal can be transmitted several hundred kilometers without any signal regeneration. At the receiver side, a wavelength demultiplexer is used to separate optical channels at various wavelengths. After channels at various wavelengths are separated, a photo detector is used for each optical channel to convert the optical signal back to an electrical signal before subsequent processing.

In each of the following three sections, an example will be presented to demonstrate how signal processing techniques can be used to improve WDM system performance.

APPLICATION EXAMPLE 1: OPTICAL WAVELENGTH INTERLEAVER DESIGN

The optical wavelength interleaver has been widely used in DWDM systems and has become an important building block for optical networks with high transmission rates [1]. Basic interleaver function is illustrated in Figure 2(a). The interleaver splits input spectrum into two interleaving output spectra as shown in Figure 2(a). By cascading interleavers, the wavelength demultiplexer described in the previous section can be implemented. Since the interleaver is a bidirectional device, it can also be used to implement a wavelength multiplexer. Major advantages of the interleaver are its high bandwidth utilization and that a narrow channel spacing interleaver is easy to manufacture when compared with other bandpass filtering technologies such as thin-film filter and arrayed waveguide grating. These advantages make the interleaver an important component in DWDM applications. Various approaches to implementing the interleaver have been proposed. Among numerous interleaver implementation approaches, the Mach-Zehnder interferometer-type interleaver and the Michelson interferometer-type interleaver are probably



[FIG2] **(a) Interleaver input and output spectra. (b) The Mach-Zehnder interferometer interleaver diagram. (c) The Michelson interferometer interleaver diagram. (d) Simulated Mach-Zehnder interferometer (red line) and Michelson interferometer (blue line) type interleaver output spectra.**

the most common. It has been shown previously that signal processing techniques can be applied to design these two types of interleavers [2], [3].

The diagram of Mach-Zehnder interferometer is illustrated in Figure 2(b). The Mach-Zehnder interferometer is a one-by-two filtering device. Its fundamental working principle can be described as follows. The input signal to the Mach-Zehnder interferometer is first split into two paths. One path of signals experiences extra delay. These two paths of signals are then mixed and resplit. This split-mix-split process can be cascaded until the desired filter spectrum is achieved. By changing splitting ratios [as k_i illustrated in Figure 2(b)] and delay lengths, various filtering function can be achieved with the Mach-Zehnder interferometer. Approaches for implementing the Mach-Zehnder interferometer-type interleaver include waveguide and use of birefringent materials.

From Figure 2(b), it is easy to identify that Mach-Zehnder interferometer is a form of finite impulse response (FIR) filter because there is no feedback path within the filter. It is well known that an FIR filter can be designed as a linear-phase filter by carefully allocating positions of its transfer function zeros on the Z-plane. With the help of signal processing techniques, optical engineers could model the Mach-Zehnder interferometer with a Z-transform model and then design a linear phase interleaver. For high transmission rate optical networks, the phase distortion introduced by optical devices becomes an important issue and is the major advantage of the Mach-Zehnder interferometer-type interleaver [3].

Unlike the Mach-Zehnder interferometer-type interleaver, which could be modeled as an FIR filter, the Michelson interferometer belongs to the category of the infinite impulse response (IIR) filter. A simplified Michelson interferometer diagram is illustrated in Figure 2(c). The input signal is separated into two directions by a 50:50 beam splitter and is then reflected by two etalons whose rear mirror has 100% reflectance. An etalon consists of two glass plates that reflect light incident upon them and that are separated by a small distance. The etalon used in the Michelson interferometer, which has partial reflective coating on the front surface and high reflective coating (R~100%) on the back surface, as shown in Figure 2(c), is referred to as the Gires-Tournois etalon [5]. These two paths of reflected signals interfere with each other and then generate two interleaving output spectra. Since each etalon reflects all incident signal power back, the Michelson interferometer is a special case of bandpass filter consisting of two all-pass filters. In most of Michelson interferometer diagrams, either the two etalons have the same thickness, or one of them is replaced by a mirror with 100% reflectance [4]. Unlike these diagrams, the Michelson interferometer illustrated in Figure 2(c) consists of two etalons of different thickness. The thickness of two etalons and their path difference with respect to the 50:50 beam splitter are assumed to be multiples of unit length represented as Z^{-1} in the Z-domain. The central frequency of two etalons might be misaligned, and a tiny path difference between two arms may then introduce a phase shift. These effects are represented by $e^{j\phi_i}$ in the Michelson interferometer filter model. Based on these assumptions, the transfer functions of the two output ports of Michelson interferometer interleaver can be represented in Z-transform format as follows:

$$\begin{aligned}\text{Port 1} =\ & \frac{1}{2}\left(\frac{\sqrt{R_1}+Z^{-n_1}e^{j\phi_1}}{1+\sqrt{R_1}Z^{-n_1}e^{j\phi_1}}Z^{-n_2}e^{j\phi_2} + \frac{\sqrt{R_2}+Z^{-n_3}e^{j\phi_3}}{1+\sqrt{R_2}Z^{-n_3}e^{j\phi_3}}\right)\\ \text{Port 2} =\ & \frac{i}{2}\left(\frac{\sqrt{R_1}+Z^{-n_1}e^{j\phi_1}}{1+\sqrt{R_1}Z^{-n_1}e^{j\phi_1}}Z^{-n_2}e^{j\phi_2} - \frac{\sqrt{R_2}+Z^{-n_3}e^{j\phi_3}}{1+\sqrt{R_2}Z^{-n_3}e^{j\phi_3}}\right).\end{aligned} \tag{1}$$

One would notice from (1) that, for the Michelson interferometer-type interleaver, its transfer function has zeros and poles. As a result, the Michelson interferometer-type interleaver could not be designed as a linear-phase interleaver [2]. However, it enjoys advantages such as compact size and higher isolation. Also, with an all-pass filter phase compensator as described in the next section, the signal phase distortion caused by the Michelson interferometer can be significantly reduced. Simulated output spectra of Mach-Zehnder and Michelson interferometers are illustrated in Figure 2(d). Notice the interleaving output spectra of these two types of interleavers.

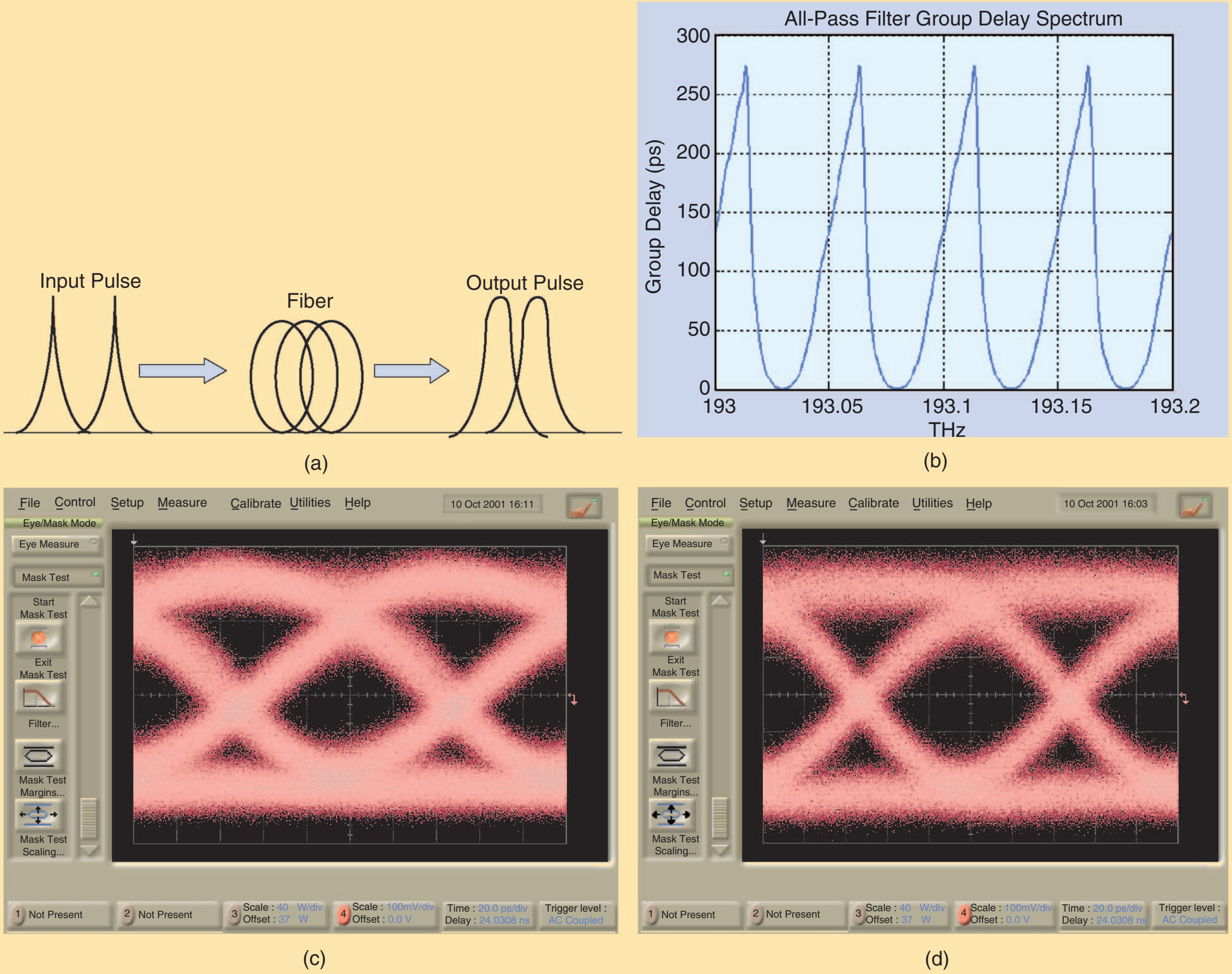
Instead of using abstract Z-transform models, many optical engineers usually use physical models to design optical devices. For example, the Jones matrix is often used to model birefringent crystal-based Mach-Zehnder interferometer [5]. Instead of allocating zeros or poles of transfer functions in Z-plane, optical engineers could optimize filter output spectrum by directly manipulating physical parameters of optical filters such as half-wave plate rotation angle and signal polarization. Although physical models can capture system characteristics precisely, some insights are hidden behind physical parameters. For example, it is easy to design a linear phase FIR filter by allocating zero locations of its transfer function in Z-plane. On the other hand, it will be difficult to design a linear phase filter by directly manipulating physical parameters of optical filter. Besides, since numerous digital filter design algorithms have been developed based on Z-transform, it will be very efficient to design an optical filter such as wavelength interleaver in the Z-plane with these algorithms and then derive corresponding physical parameters from the filter transfer function in the Z-plane. To derive physical parameters based on a filter's transfer function in the Z-plane is usually straightforward [2]. Otherwise, different design algorithms need to be developed for the same type of filter implemented with different physical implementation methods.

EXAMPLE 2: ALL-PASS FILTER FOR DISPERSION COMPENSATION

As mentioned previously, optical fiber has chromatic dispersion that distorts signal phase. During optical signal transmission in optical fiber, signal components at different wavelengths experience different group delay; therefore, the transmitted optical pulse is broadened, as illustrated in Figure 3(a). This phenomenon is referred to as chromatic dispersion, and it could increase bit error rate in optical communication systems. The definition of chromatic dispersion is the derivative of group delay with respect to wavelength; the unit commonly used is picoseconds per nanometer. The optical communication system tolerance for chromatic dispersion is inversely proportional to the square of system transmission rate. For example, while a 10 Gb/s channel can tolerate dispersion of 1,200 ps/nm, a 40 Gb/s channel can only tolerate dispersion of 75 ps/nm. Therefore, the chromatic dispersion is an extremely important problem in the high transmission-rate optical communication system design.

To compensate chromatic dispersion, a dispersion compensation fiber (a special fiber with dispersion opposite of the standard fiber dispersion) is offered as the most popular solution. Dispersion compensation fiber is a reliable and mature technology. However, it has some serious disadvantages, such as having a large footprint, having a high insertion loss, causing nonlinear distortion when input signal power is high, and others. Alternatively, several dispersion compensation schemes have been proposed; the one based on an all-pass filter is probably one of the most popular alternative dispersion compensators. It has advantages such as compact size, low insertion loss, and no nonlinearity under high input power [6].

The all-pass filter has been widely used to compensate phase distortion by signal processing researchers. This is a special filter with flat magnitude spectrum and nonlinear phase spectrum, so it can compensate phase distortion without affecting magnitude spectrum of signals. One such filter used in optical communication is the Gires-Tournois etalon described



1 Not Present
2 Not Present
3 Scale : 40 W/div Offset : 37 W
4 Scale : 100mV/div Offset : 0.0 V
Time : 20.0 ps/div Delay : 24.0308 ns
Trigger level : AC Coupled

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[FIG3] **(a) The fiber chromatic dispersion effect on optical pulse. (b) Simulated group delay spectrum of an all-pass filter for chromatic dispersion compensation. (c) Output signal eye diagram of an 80-km 10-Gb/s optical link without dispersion compensation. (d) Output signal eye diagram of an 80-km 10-Gb/s optical link whose dispersion is compensated by an all-pass filter.**

previously. The group delay spectrum of the Gires-Tournois etalon can be represented as

$$GD(f) = \frac{(1-R)(2d/c)}{1+R+2\sqrt{R}\cos(2\pi f(2d/c))}, \quad (2)$$

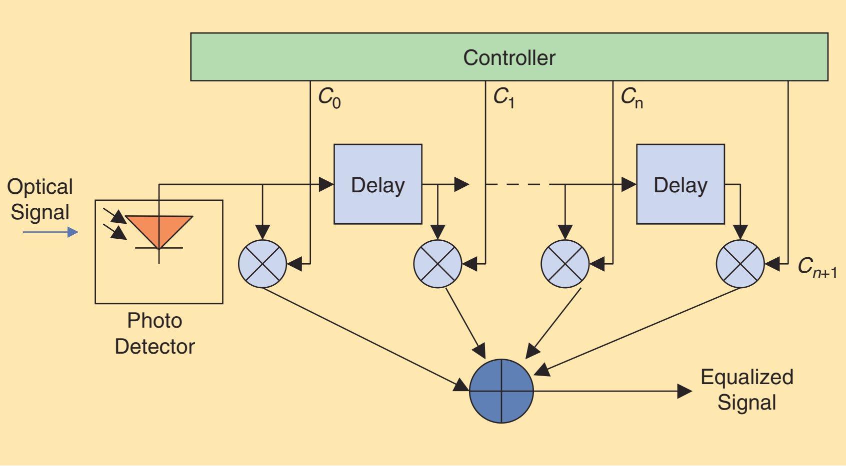
where R is the reflectance of etalon front mirror, c is the speed of light, and d is the etalon optical thickness. Although an all-pass filter consisting of Gires-Tournois etalons could be designed from the physical model illustrated in (2), representing the same filter with a transfer function in the Z-plane would allow optical engineers to use all-pass filter design algorithms developed by signal processing researchers to design a dispersion compensator. Just like the Mach-Zehnder and Michelson interferometers introduced in the previous section, the transfer function of Gires-Tournois etalon could be represented in the Z-plane as

$$\frac{\sqrt{R}+e^{j\phi}Z^{-1}}{1+\sqrt{R}e^{j\phi}Z^{-1}}. \quad (3)$$

By cascading several Gires-Tournois etalons, each of which has a carefully designed coating [changing the value of R in (3)] and thickness [changing the value of $e^{j\phi}$ in (3)], engineers can increase the dispersion compensation bandwidth and the amount of dispersion compensation. Figure 3(b) shows a simulated group delay spectrum of a dispersion compensator consisting of seven cascading etalons with different front surface coatings and thicknesses that compensate for the chromatic dispersion caused by 75 km of standard single-mode fiber.

Due to its periodic spectral properties shown in Figure 3(b), the all-pass filter dispersion compensator can be used for multichannel dispersion compensation. Therefore, it would be a great choice for WDM system dispersion compensation. To demonstrate the usefulness of the all-pass filter compensator, the measured output signal eye-diagram of an 80-km long optical link without dispersion compensation and one of the same link compensated by an all-pass filter are shown in Figure 3(c) and (d), respectively. These results clearly demonstrate that an all-pass filter could enhance signal quality damaged by fiber dispersion. With implementation technologies such as microelectromechanical systems (MEMS), the all-pass filter dispersion compensator could be made as a tunable device. This feature makes the all-pass filter an important dispersion compensation technique since dispersion variation caused by environment changes is one of major issues for high transmission rate optical systems.

It is noteworthy that, in addition to fiber dispersion, the all-pass filter could also be used to compensate for device dispersion such as the optical interleaver. The Michelson interferometer introduced in the previous section could not be designed as a linear phase filter, but its dispersion could be significantly reduced by an all-pass filter dispersion compensator.



[FIG4] **A possible electronic equalizer diagram for optical communication systems. The feedback circuit is not displayed.**

EXAMPLE 3: ELECTRONIC EQUALIZER

In addition to chromatic dispersion, there are other kinds of signal distortion in optical communication systems such as polarization mode dispersion (PMD). This form of dispersion is caused by the fact that optical signals of different polarizations experience different delays during transmission. In addition, polarization dependent loss (PDL) also causes signal distortion. This, in turn, is caused by the fact that signals with different polarizations experience different attenuations. Some of these distortions change continuously; therefore, a compensator with some feedback control is very desirable. Different optical compensators might be necessary for different optical signal distortions such as chromatic dispersion, PMD, and PDL. To compensate for various signal distortions with a single adaptive optical circuit might be achievable but would be rather complicated and difficult to implement. In addition, most of proposed adaptive optical compensator approaches are not yet sufficiently mature for mass production. On the other hand, adaptive electronic equalizers have been applied for a long time, numerous algorithms have been developed, and the DSP processor is a mature technology for mass production. It would be beneficial if a single adaptive electronic equalizer could be used to compensate for all of the distortion happening in the optical link. Since optical signals usually need to be converted to electrical signals for electronic devices such as a computer, TV, and telephone, in most cases, what really matters is the signal quality of electrical signal after O/E conversion. A simplified electronic equalizer as illustrated in Figure 4 is designed for this purpose. After the demultiplexer, the optical signal is converted to electrical signal, then an electronic equalizer can be used to compensate for signal distortion caused by numerous factors such as chromatic dispersion and PMD [9]. A feedback scheme (that we do not display in Figure 4) could be used to track system changes to optimize the equalizer performance.

Although a straightforward and elegant approach, the electronic equalizer has an inherent shortcoming. Some information about the optical signal such as polarization and phase is lost during the O/E conversion. As a result, the electronic equalizer illustrated in Figure 4 has a limitation on its performance. A special modulation scheme could be used to solve this problem to some extent. It has been demonstrated that when a single side band modulation scheme is applied in optical systems, the performance of an electronic equalizer can be improved significantly [10].

CONCLUSION

Optical communication plays a significant and increasing role in our society. The public demand for higher network speed requires an optical backbone network with larger capacity. Accompanying high transmission-rate optical communications system are severe technical specifications for optical devices and systems. Many popular optical devices could be represented with a digital filter model as described in this article. Use of well-developed signal processing techniques and algorithms to design these optical devices is a wise use of existing technology. As demonstrated in this article, signal processing could play an important role in the development of advanced optical communication systems. However, as demonstrated in the case of an electronic equalizer, some optical system characteristics may require special attention if signal processing techniques are to be applied successfully. Therefore, interdisciplinary cooperation between researchers in optics and signal processing will be crucial for optical communications to fully benefit from signal processing.

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DSP HISTORY

(continued from page 81)

SPM: *Let us wrap up by looking in the past with a thought for the future: your invention of the microprocessor was a major breakthrough. Where do you consider that breakthroughs are needed now in DSP?*

Dr. Hoff: The more speed we can offer in both the DSP and the associated A/D and D/A conversions, the more applications we will find. When we combine traditional DSP with other logical processing such as data encryption and addition or elimination of redundancy, we can expect to improve reliability and security of all of our communication channels. I would also like to see more natural language processing, including recognition, understanding, and translation. In particular, fast and accurate language translation would seem to offer a huge potential for improving human communication and cooperation, and better machine understanding of language should help make computers even more useful.

SPM: *Thank you.*