PHOTONICS
THE KEY TO HIGH-SPEED INFORMATION SYSTEMS

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ABSTRACT

It seems like just yesterday that 10 Gb/s (OC-192) transmission was the norm in data rates with slower data rates disappearing! The particular bit-rate jump to 40 Gb/s (OC-768) is not a trivial task. Electronic designers now face serious complexities as they push the technology to the limit. Issues such as chromatic dispersion and polarization mode dispersion are placing more stringent requirements on fiber optics and associated components. The requirement to gather and transfer data at faster and faster rates has spurned an evolution in the thought processes of Photonic engineers. It appears that to handle the ever-increasing bandwidths, Photonic techniques are the way to go! Sophisticated analog-to-digital converters and polymer-based modulator systems are now being designed and tested in Air Force government laboratories. Only time will tell if these designs can handle the voluminous amounts of data!

RF SIGNAL GENERATION

The generation and distribution of analog radio frequency (RF) signals are critical to both civilian and military applications; antenna remoting, antenna signal distribution, true time delay, beamforming and RF signal generation. For space-based systems and airborne platforms issues of size, weight, electromagnetic interference (EMI) and differential loss are of great concern. These concerns are further amplified as system requirements evolve to higher bandwidths and system location choices are in unmanned, air breathing or space-based platforms.

There are several advantages which *photonics* offers over an all-electronic implementation. Optical fiber exhibits low loss and high bandwidth. The RF signal attenuation in optical fiber is less than 0.8 dB/km up to and including frequencies greater than hundreds of GHz. Metallic cable has high loss and is highly dispersive. Fiber optic cable is mechanically flexible and lightweight! Fiber optic cable weight is approximately 1/250 of the weight of metallic waveguide (frequency dependent), and 1/10 the weight of coaxial cable. Fiber optic cable size allows up to 60 fiber optic 'strands' in the space of a single coaxial cable! Fiber optics has the additional advantage that it is immune to electromagnetic interference such as surface generated electromagnetic pulse. Fiber optics is much less phase-temperature sensitive than metallic cable; over a temperature range of 125 °C (from –50 °C to 75 °C), fiber optic cable will exhibit a phase variation of about 10 /100ft, while a high performance coax-cable will undergo about 300 phase change/100ft.

These merits indicate that *photonics* is a relevant technology. However, at this point in time, it is not yet a fully 'mature' technology. *Photonic* link performance does not meet many military system performance requirements. Although fiber optics is now frequently used in commercial communications, it is not widely implemented in military systems. It should be noted that the requirements for military systems are much more stringent than for the commercial world! Consequently, the military cannot rely on commercial off-the-shelf (COTS) components and links to meet its needs.

MICROWAVE LINKS AND COMPONENTS

The basic *photonic* link consists of an optical transmitter, an optical fiber transmission media, and an optical receiver. (Figure-1) The optical transmitter is either a directly modulated laser or an optical source with an external modulator. *Gain, Noise Figure, and Spur Free Dynamic Range* are the key performance characteristics, which describe a link system in either an optical or metallic implementation. For example, the military would desire (for frequencies less than 20 GHz): $G > 0$dB, $NF < 6$dB, and $SFDR > 115$ dB/Hz$^{2/3}$. These are reasonable requirements, although in many cases, higher dynamic range is required! Current technology does not meet these goals! A state-of-the-art *photonic* link may have: G=-18 dB, NF= 27 dB,

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and *SFDR*= 113 dB/Hz$^{2/3}$. The key to obtaining the required system performance is improved components, mainly the modulator and photodetector which are the information transmitter and information receiver of the link!

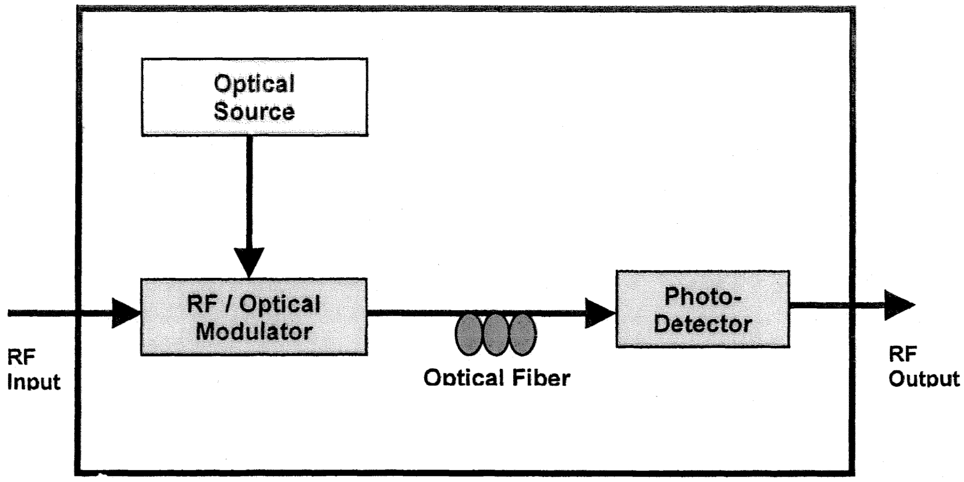


Figure 1: RF Fiberoptic Link

MODULATOR CHARACTERISTICS

The main external modulator parameter, which characterizes the modulator and overall system performance, is the V_π value, which is the half-wave voltage. (Figure-2) shows the dependence of the noise figure and link gain on the modulator V_π value. We assume a 50Ω modulator, a 50Ω detector, and 16mA detector current. The lower the V_π, the higher the gain and lower noise figure! Current technology is centered around the 3-7 volt region. An *optimal* modulator efficiency would involve a V_π voltage on the order of 1.0 volt or less (which would provide for a *near* lossless link with low noise figure! Low V_π modulators are seen to be the technical barrier to obtaining the desired link gain.

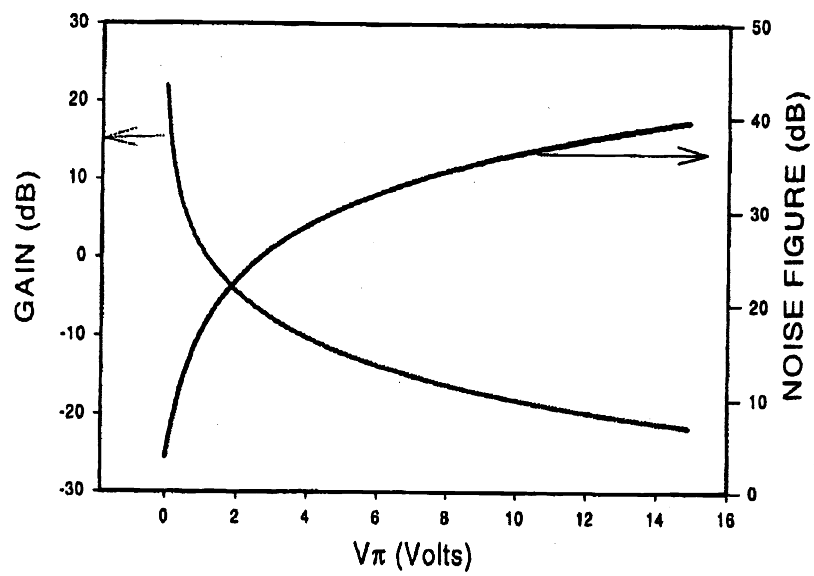


Figure 2: Link Gain and Noise Figure vs. Vπ

Lithium niobate is a mature technology! Lithium niobate modulators utilizing an interferometric Mach-Zehnder design have been the standard external modulators for optical links. Work at the Naval Research Laboratory has demonstrated a V_π of 3 volts. However, lithium niobate modulators suffer from RF/optical velocity mismatch and achieving a $V_\pi < 1$ V seems unlikely!

Alternative modulator materials and designs need to be considered and developed. Inorganic crystals with large electro-optic coefficients are providing interesting alternatives. Other modulators, which are currently under development, include electro-optic *polymers* and *semiconductor* modulators. Both of these technologies have provided low V_π as well as low cost and small volume devices. However, **durability** and optical throughput are areas of concern and investigation! [The semiconductor devices offer the advantage of being easily integrated with electronics.] Due to the modulation technique used, Mach-Zehnder type modulators are limited to approximately 113 $dB/Hz^{2/3}$ SFDR. For higher dynamic range links, alternative designs are required. This may be accomplished through linearization of the Mach-Zehnder. However, *linearization* approaches have been complicated, unreliable, and frequency/temperature dependent. *Electro-absorption* modulators offer the potential of high dynamic range, but additional 'technical exploration' is required! [Electro-absorption modulators may also be limited in optical power handling capability.]

Ultrahigh modulation efficiency could be achieved using '*Whispering-Gallery-Mode*' microspheres. These modulators would offer increased bandwidth, relative to their nearest competitor, which are traveling-wave electro-optical modulators. The introduction of such devices could increase the bandwidths and reduce power demands of a variety of both free-space and guided-wave communication, sensing, and signal-processing systems that utilize radio frequency (typically, microwave) modulation of optical carrier signals!

The 'whispering-gallery' modes of a dielectric microsphere are resonance modes in which electromagnetic fields are confined (by internal reflection) to an interior region within about 10 μm of the surface of the sphere. For example, for a microsphere with a diameter of > 10 μm, the dimension of the resonator is much larger than the wavelength of light! Therefore, the loss due to the finite curvature of the resonator is *negligible*, resulting in a resonance quality factor (Q) that is high (e.g.; Q=104 to 107) and is limited mainly by the attenuation of the light in the dielectric material! In very simplistic terms of a proposed modulation scheme, a radio frequency (RF) [microwave or millimeter wave] field is applied to a microsphere in which an optical signal propagates in a 'whispering-gallery' mode. Per the electro-optical effect, the *electric component* of the radio-frequency field would alter the speed of propagation of (and thereby *modulate*) the optical signal. It has been estimated that the maximum useable modulation frequency would be increased from = 50 GHz in the traveling-wave case to = 100 GHz in the microsphere case! There, still of course, is much to be investigated before such devices are used in the military and/ or commercial sectors!

DETECTOR CHARACTERISTICS

Detectors capable of *high power, high-speed performance,* and *improved efficiency* are needed for RF link systems. (Figure-3) shows the overall link gain as a function of photo-detector current. To achieve high-speed performance, the detector area

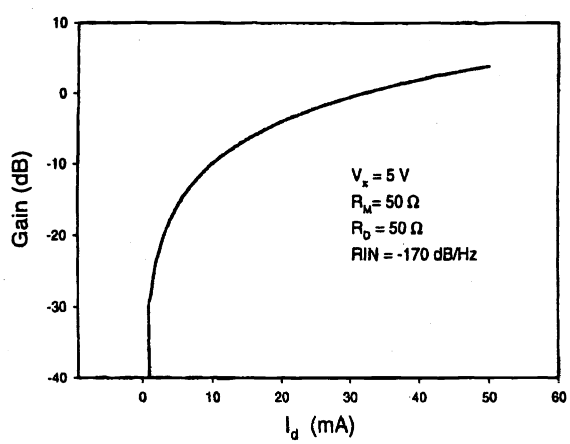


Figure 3: Link Gains vs. Photodetector Current

is reduced in size, which limits the current. Traveling wave detector designs allow for higher current, but compromise the detector bandwidth. Presently, high-speed detectors are limited to about 10 ma. The 'goal' for the photo-detectors for the RF links is a high frequency photo-detector with current capability of greater than 20 ma.

ANALOG-to-DIGITAL CONVERTERS (ADC)

Analog-to-Digital converters (ADC) have wide spread application in both commercial and military systems. These systems cover a wide range of continuous-time analog signals including radar, electronic warfare, communications, and medical imaging. In all of these systems the analog signal must be converted into a discrete-time digital signal which is then processed using digital signal processing techniques. The development of ADCs has not kept pace with the rapid advancements of digital processors. For example, it has been shown that it takes approximately eight years for each improvement of 1.5 bits of digital resolution! (Figure-4).

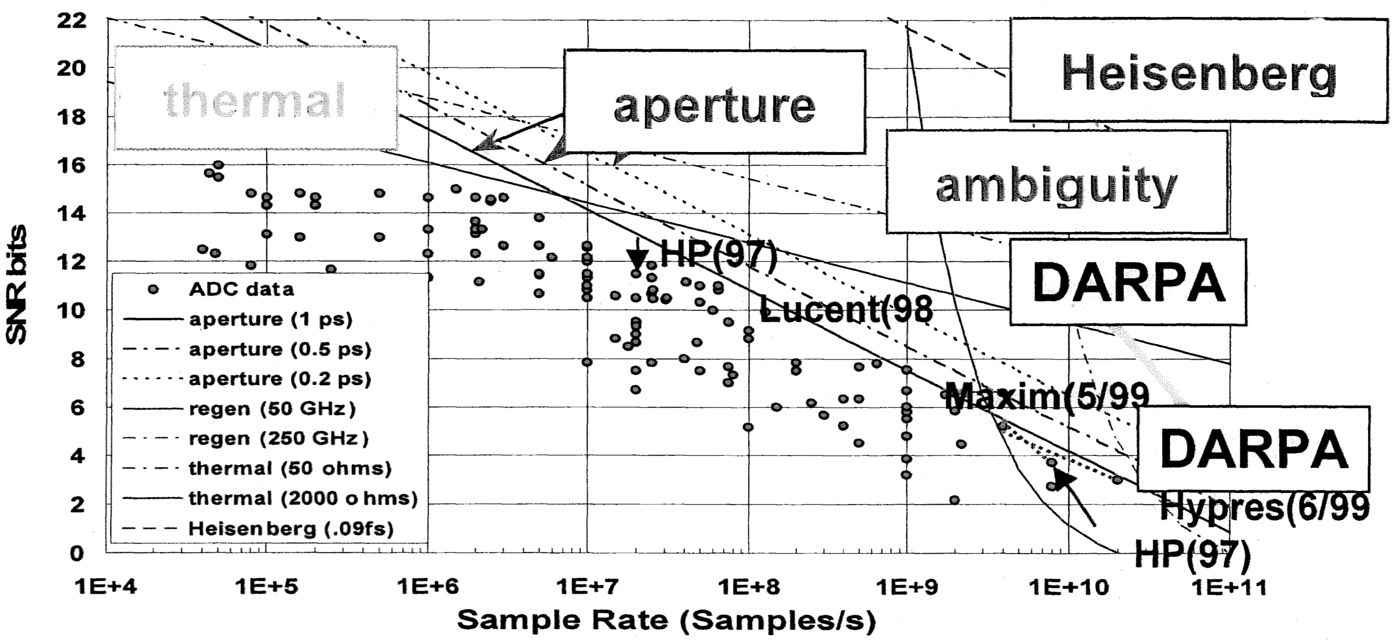


Figure 4: Electronic ADC Evolution / "The Walden Wall"

However, it should be pointed out that as the sampling rate of the ADC is doubled there is a loss of one bit of resolution! The practical limitations of electronic ADC development are due to three common noise sources:

- Thermal Noise limits ADC operation below 2 MS/s. This is a result of voltage fluctuations in any resistive circuit elements at a given temperature
- Sampling time fluctuations or aperture uncertainty limits ADC operation between 2 MS/s to 4 MS/s
- Comparator ambiguity appears to limit speed with which the ADC electronic circuitry can respond to small changes in voltage.

The limitations in electronic ADC development have led to an increased interest in using novel opto-electronic techniques to overcome these barriers. The achievement of narrow sampling pulsewidths at high sampling rates with low jitter by photonic systems will allow for a simultaneous increase in both the conversion speed and accuracy of ADCs. The increase in ADC performance will also lead to a decrease in the complexity of receiver systems. A typical receiver is currently limited by the speed of the ADC. Single or multiple down conversion stages are often required to convert the frequency of the received analog signal into a frequency that can be processed by the ADC. The down conversion process requires many analog components including local oscillators, mixers, and filters. Improved ADC performance will eliminate these components, which often consume large amounts of power and are typically unreliable. However, the revolutionary advancement of ADC performance through the use of photonics requires the development of compact, low noise, and low power systems.

There has been much recent interest in the use of photonics to aid in the signal conversion process. Two unique photonic ADC architectures will be briefly mentioned:

- One idea uses an array of passive photonic semiconductor saturable absorbers to convert the signal
- The other idea uses a unique opto-electronic sampling and quantizing circuit to convert the analog signal at sampling speeds up to tens of gigahertz!

POLARIZATION

As the bit rate increases, information (communication) networks become increasingly sensitive to polarization-related impairments such as polarization mode dispersion in optical fibers, polarization-dependent loss in passive optical components, polarization-dependent modulation in electro-optic modulators and polarization-dependent gain in optical amplifiers. Communications systems with polarization-induced problems require dynamic polarization controllers that are fast and have very low losses. {Figure-5}

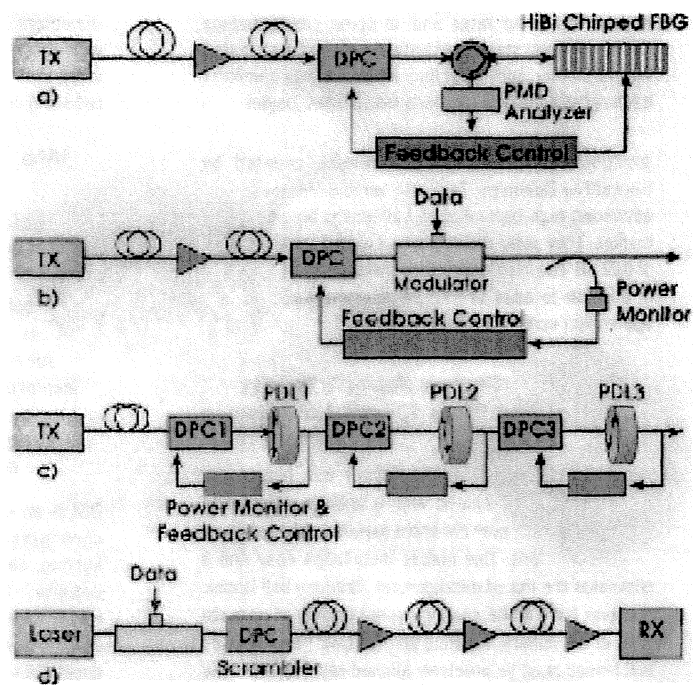


Figure 5: Dynamic Polarization Controllers

a) polarization mode dispersion mitigation using a chirped HiBi fiber grating

b) a polarization stabilization scheme

c) polarization-dependent-loss compensation; and d) polarization-dependent-gain mitigation.

With the advent of dense wavelength division multiplexing and higher-bit-rate transmission, analyzing polarization mode dispersion became essential in high-speed, dispersion- compensated digital and analog long haul networks. Reducing and compensating all dispersion sources is a high priority, particularly as erbium-doped fiber amplifiers increases the length of fiber links. In fact, measuring and characterizing polarization mode dispersion is essential both after manufacturing and after cabling and installation. Mechanical bends and stresses change the local birefringence of the fiber and therefore affect its polarization characteristics.

The cause of polarization mode dispersion in single-mode fiber is asymmetry, which is induced during manufacture. By monitoring this parameter, manufacturers can characterize the fiber-drawing process to minimize undesirable birefringence.

Fiber stress creates additional dispersion during cabling, even if individual fibers are OK. In a high-fiber-count cable, the inner fibers show higher polarization mode dispersion delays than the outer fibers.

Component qualification is a challenge because of the very short fiber length in a component. It requires technology that can measure very low dispersion within a narrow bandwidth. Cable installers characterize the installation's polarization mode dispersion contribution so that they can re-adjust and protect their operations. Quantifying polarization mode dispersion is useful when planning network system upgrades that will operate at higher transmission rates. Untested fiber links with high dispersion delays can degrade an entire network's performance.

Manufacturer requirements are clearly very different from field testing needs. Fiber and component manufacturers are continuously improving their processes and want to measure ever-lower polarization mode dispersion values in their devices. Also, there is a strong premium on measurement speed on the production floor. Manufacturers anticipate that they will need to measure polarization mode dispersion delays down to the femtosecond range in new fibers and components. To reach that resolution level, instruments must completely analyze the polarization states and use fully polarimetric techniques that measure all three Stokes polarization parameters as a function of optical frequency.

The industry uses two measurement techniques: Jones Matrix Eigenanalysis later termed the "matrix technique", and Poincare Sphere Analysis, later termed the "sphere method". Both techniques involve several minutes of data acquisition with a tunable laser source and a polarimeter. Because polarization mode dispersion is very dependent on environmental changes, such as impact- or vibration-induced stresses, temperature variations, etc., measurements performed over several minutes can be problematic.

Femtosecond polarization mode dispersion analysis based on the sphere method uses a nonpolarized broadband source with a Fourier spectrometer and a polarimeter. A high-precision polarization controller determines the input states of polarization. The broadband source provides all the wavelengths simultaneously within the working spectrum range. In a few seconds, the system can acquire the data it needs for polarization analysis. The resulting measurement is therefore more resistant to external variations. An amplified spontaneous emission light source can increase the dynamic range up to several tens of decibels, making it possible to test fiber spools up to a couple of hundred kilometers in length.

Early polarization mode dispersion analyzers were designed for laboratory environments. These bulky instruments generally performed well in controlled laboratory settings but had severe limitations for field applications, particularly in testing fibers with ends 150 km apart. The interferometric method changed the reality of field testing by delivering fast, reliable measurements independent of the environmental conditions. The interferometric method, based on a Michelson interferometer, uses a polarized LED source to simultaneously perform the measurement over the entire signal spectral bandwidth. The movable interferometer arm creates an interference pattern relating to the average polarization mode dispersion delay. The interferometric method uses only one state of polarization and is very fast – typically around 15 seconds. The Michelson interferometer does have a few limitations that restrict it to fiber testing: The minimum measurement range is limited to 0.12 ps, per the International Telecommunication union standards, and it is unable to characterize narrowband components.

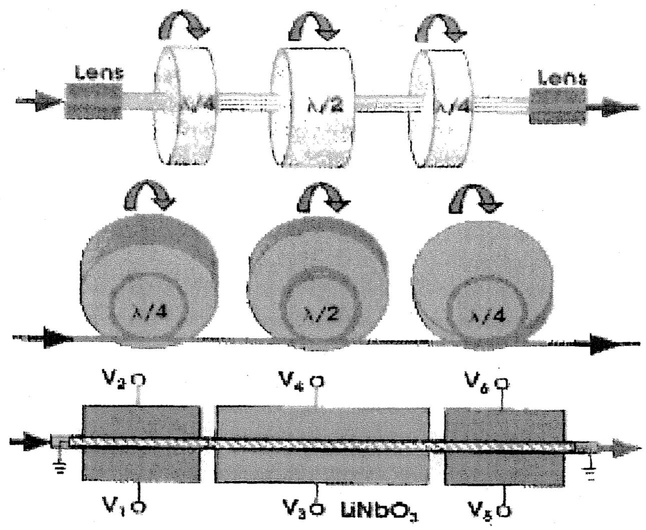
Portable polarization mode dispersion analyzers are now strong, rugged and user-friendly, even under adverse test conditions. They also provide an impressive dynamic range, testing fibers as long as 250 km. The limitations on higher dispersion-measurement ranges and long fiber testing clearly do not influence service providers, cable installers or cable manufacturers, who use the technology for quick, average measurements.

Imperfections in optical fibers cause these polarization impairments. If the fibers were perfect, the polarization state of the light signal they carry would remain constant, and polarization effects could easily be eliminated. Unfortunately, the polarization state of light propagating in standard communication fiber varies along the fiber because of random birefringence from thermal stress, mechanical stress and irregularities of the fiber core. Worst of all, the induced birefringence changes with temperature, pressure, stress and other environmental variations, marking polarization-related impairments change over time. Because polarization-induced penalties are time-dependent, mitigation of impairments {Figure-6} must be dynamic and adaptive to random time variations. An ideal dynamic polarization controller would offer low insertion loss, high return loss and several other parameters.

High speed is essential for tracking fast polarization variations such as those caused by passing locomotives in fibers laid along railway tracks or by ocean waves in transoceanic fiber trunks. In field measurements using a polarization mode

Figure 6

Polarization controllers that use multiple wave plates with fixed retardation and variable orientation angles tend to be slow and wavelength-sensitive. From top: the free-space optics approach, the fiber coil ("Mickey Mouse Ears") approach, and the electro-optic waveguide approach.



dispersion transient recorder, fluctuations with a time scale of a few milliseconds have been observed. Therefore, the response time of the dynamic polarization controller must be less than 1 ms. In practice, a response time less than 100 μs is sufficient. Activation loss measures the additional insertion loss caused in activating the device. It is defined as the difference of the maximum and minimum insertion losses of the device considering all possible activation conditions. This is important because polarization compensation schemes use feedback signals to activate the controller. The activation-induced loss causes errors in the feedback signal and directly degrades the performance of the compensation apparatus.

Wide operation bandwidth is important for dense WDM systems that cover a broad wavelength band. Wide-bandwidth polarization controllers function equally well for many wavelength channels, simplifying system design, reducing system cost and enabling the expansion of bandwidth.

Uninterruptibility is also critical for dynamic polarization controllers in optical networks because any polarization reset may cause unacceptable signal outage. Today's commercial polarization controllers fall into three technology classifications: multiple wave plates with fixed retardation but variable orientation angles; a single wave plate with variable retardation and orientation; and multiple wave plates with fixed orientation and variable retardation. Controllers based on wave plates of fixed retardation are wavelength-sensitive. Those that rely on physical rotation are generally slow. Other than these fundamental limitations, all three approaches work reasonably well in principle. However, implementation determines the performance, cost and reliability of the devices.

With varying wave plates {Figure-6} a half-wave plate is sandwiched between two quarter-wave plates and the retardation plates are free to rotate around the optical beam with respect to each other. The first quarter-wave plate converts arbitrary input polarization to a linear polarization. The half-wave plate then rotates the linear polarization to a desired angle so that the second quarter-wave plate can translate the linear polarization to any desired polarization state. In this approach, the retardation of the plates is fixed, but the relative angles of the retardation plates can vary. Commercial applications of this triple-wave-plate approach have produced respectable results.

The technique does have drawbacks: collimating, aligning and refocusing are time consuming and labor intensive. Also, the wave plates and microlenses are expensive and need antireflection coatings or angle polishing to prevent back-reflection. Insertion loss is high because the optical beam has to be coupled out of one fiber and refocused into another. Furthermore, the wave plates are inherently wavelength-sensitive (any fractional wave plate is always specified with respect to a particular wavelength), making the device sensitive to wavelength variations. Finally, electrical motors or other mechanical devices rotate the wave plates, limiting the controller speed.

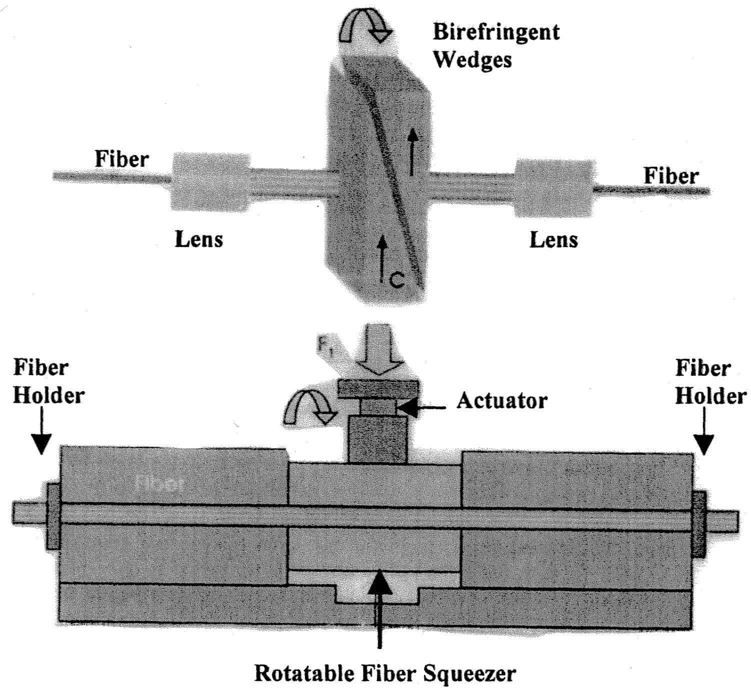
An all-fiber controller based on this mechanism reduces the insertion loss and cost. In this device, three fiber coils replace the three free-space retardation plates. Coiling the fiber induces stress, producing birefringence inversely proportional to the square of the coils' diameters. Adjusting the diameters and number of turns can create any desired fiber wave plate. The device still suffers from sensitivity to wavelength and low speed. In addition, because bending the fiber generally induces insertion loss, the fiber coils must remain large, and the resulting device is generally bulky. Therefore, the use of these "Mickey Mouse Ear" controllers is primarily limited to laboratories.

For network deployment, speed is essential, and physically rotating wave plates cannot meet the need. For this reason, lithium-niobate-based high-speed polarization controllers were developed. One such controller comprises three waveguide sections, two of which simulate a quarter-wave plate, and one of which simulates a half-wave plate. However, instead of rotating the wave plates, two voltages and the electro-optic effect determine the relative orientation (effective optical axis) of each. Proper voltage adjustments can achieve endless rotation of each wave plate.

Unfortunately, the price for this speed increase may not be acceptable for network applications. High insertion loss (~3 dB), high polarization-dependent loss (~0.2 dB), high activation loss (~0.15 dB) and high cost (>$5000) are the major disadvantages. The device also has at least nine parameters to optimize, making implementation complicated and costly. In an alternative approach, a Babinet-Soleil compensator {Figure-7} can convert any input polarization state into any desired output polarization state. The heart of such a device is a composite wave plate made from two birefringent crystal wedges. The thickness (and therefore the total retardation) of the wave plate varies by sliding the wedges against one another. The orientation of the composite wave plate also can rotate around the optical beam. Compared with the previous device, this one has the advantage of insensitivity to wavelength. However, it suffers from high cost, high insertion loss and low speed.

Figure 7

From top: a free-space optics approach, and an all-fiber approach with rotatable fiber squeezer.



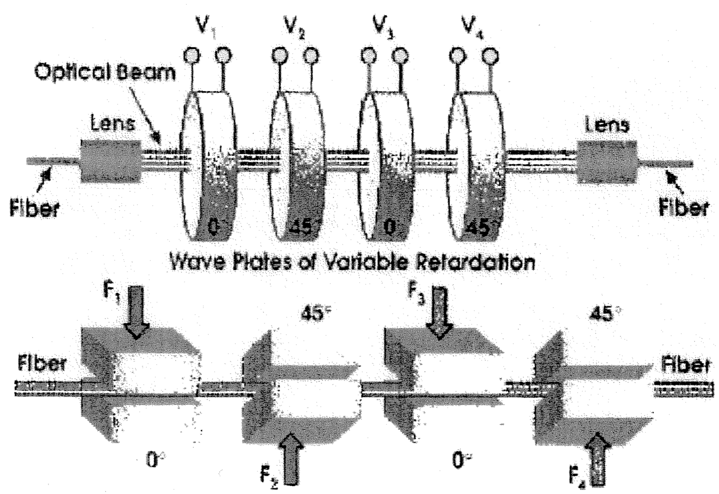
To reduce the cost and insertion loss, an all-fiber polarization comptroller based on the Babinet-Soleil compensator principle was developed. The device comprises a fiber squeezer that rotates around the optical fiber. Applying pressure to the fiber produces a linear birefringence, effectively creating a fiber wave plate whose retardation varies with the pressure. Simple "squeeze and turn" operations can generate any desired polarization state from any arbitrary input polarization. The device is small and wavelength-insensitive, especially compared with the "Mickey Mouse Ear" controllers. This makes it useful for integration into WDM modules. However, similar to the controller that rely on physical rotation, this device is too slow for dynamic polarization-mode dispersion compensation in fiber optic networks.

Polarization controllers can also be made with multiple free-space wave plates oriented 45° from each other. The retardation of each wave plate varies with an applied voltage; however, the orientation angles are fixed. These variable-retardation wave plates can be made with liquid crystals, electro-optical crystals or electro-optical ceramics. The disadvantage of the liquid crystal device is low speed, and the electro-optical one generally requires high operation voltages. Like other devices based on free-space optical components, they generally have high insertion loss, high activation loss, and high cost. In addition, their optical bandwidth is limited because both the antireflection coatings and microlenses have limited bandwidths.

An all-fiber device based on the same operational principle would reduce the insertion loss and cost. The retardation of each wave plate varies with the pressure of each fiber squeezer. {Figure-8} The challenge is making the device reliable, compact, and cost-effective. The fiber squeezer controller can also work as a polarization scrambler to effectively randomize polarization states. With a built-in resonant enhanced circuit, the half-wave voltages of the device at scrambling frequencies are reduced to only a few volts. With properly selected driving parameters, the scrambler has achieved polarization sensitivity of less than 0.05 dB and a degree of polarization less than 1 percent.

Figure 8: Multiple Wave Plates with Fixed Orientation

The free-space optics approach (top) has voltage, insertion loss, cost and bandwidth limitations, but an all-fiber "squeeze" solution (bottom) is fast, reliable and low-cost.



This feature could be used to eliminate an instrument's polarization sensitivity. Some optical instruments, such as diffraction-grating-based optical spectrum analyzers, are sensitive to the polarization state of the input light. Scrambling the input polarization can remove the measurement uncertainties this causes.

CONCLUSION

The limitations in electronic development has led to an increased interest in using novel optoelectronic techniques to overcome many of the barriers described above. The achievement of narrow sampling pulsewidths at high sampling rates with low jitter by photonic systems will allow for a simultaneous increase in both the conversion speed and accuracy of ADCs. Inorganic crystals with large electro-optic coefficients, electro-optic polymers, semiconductor modulators, and microspheres are currently being investigated in hopes of lowering V_π, reducing the volume, and increasing the bandwidth! There is still much to be investigated before such devices are used in the commercial and military sectors!

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