Photonics for time delay in communication systems

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Abstract. The design of some communication systems requires the implementation of time delays within the system. These time delays can be accomplished with a variety of optics technologies, which could be readily fabricated and integrated into the communication system without significant impacts on the system design. We describe three different potential applications of optics designs, which could be implemented to accomplish the time delay requirements associated with communication systems. One application would be in Ku/Ka band phased array antennas, where the optics application provides the time delay to the various transmit/receive units in the phased array to accomplish beam forming and switching. Another application would be in an aircraft interference cancellation system. Yet another application would be in a satellite communication test system, where the propagation time to the satellite (for synchronous satellites a nominal 36,000 km) needs to be simulated for ground testing with the earth terminals. Optical modules could be used for some applications, and optics technologies have the potential to be used for a wide range of applications in communication systems. [DOI: 10.1117/1.1372704]

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1 Ku/Ka Band Phased Array Antennas

There have been recent development efforts to integrate a photonics module into phased array antennas as the true time delay (TTD) module.[1–4] The time delay requirements for this use can be considered relatively small, ranging from 1 ps to 50 ns, or 0.3 mm to 15 m in free space, for most phased array antenna (PAA) applications.

In PAAs, specific time delay lines are integrated into the antenna to compensate for the wavefront differences resulting from the propagation from each of the PAA's individual emitters. In general, the maximum delay time required in a PAA is comparable with the antenna's size. For a large PAA it is generally beneficial to partition the array into a number of subarrays, and possibly into multiple stages of subarrays, to simplify manufacturing. This is accomplished by making use of structural symmetry and by cutting down the maximum delay times.

Whether a PAA is called ''small'' or ''large'' not only depends on the physical size of the array but also on the electrical size measured in wavelength (λ). The number of elements and the required separation of the elements drive the size of the antenna. Normally, elements are separated by less than a half wavelength to avoid grating lobes in the antenna pattern. For example, 10 m is small if the working wavelength is 10 MHz, while 10 m is large if the frequency is 1 GHz.

For the Ku/Ka frequency band, roughly from 10–30 GHz with a wavelength between 1 and 3 cm, a practical design could use from 4 to 16 elements in each subarray building block. The time delay would then be what is required for this subarray. Larger arrays can then be designed by putting together a number of subarrays. With this design philosophy, the maximum time delay requirements range from 10 cm to 1 m, including the ''effective'' delay to compensate for the time delay difference among different emitter elements and the ''extra'' delay to shape the delay lines layout pattern (in the waveguide case) or to accommodate other practical considerations. One design approach for this application is to use optical TTD lines made out of polymeric waveguide circuits[1] and electrically switched using high-speed photodetectors.

The polymeric waveguide technology is conceptually hybrid, and it provides the possibility for large-scale optoelectronic integration on a substrate in a cost effective manner. An optical waveguide grating coupler is a candidate technique for coupling out the RF modulated optical waves into photodetectors. The unique nonblocking feature of gratings allows a large number of optical fanouts along the waveguide propagation, with each fanout providing a TTD. The application of polymeric waveguide technology to generate the time/phase delays necessary to implement a phased array antenna has the potential of producing a very high quality phased array antenna system at significant cost and weight savings.

2 Aircraft Radio Interference Cancellation System

The radio has provided aircraft a broad range of capabilities to aid in safely completing missions. For many aircraft the mission is simply flying safely from one location on the earth's surface to another. Even a simple aircraft installation now includes UHF and VHF radios for voice communications, a GPS receiver to aid in navigation, various onboard transponders, and various types of navigational aids, not including unique communications equipment.

For some of the larger aircraft that have military missions, and for many commercial passenger aircraft, there is a growing number of communication requirements. Use of the available frequency spectrum by an expanding number of users has forced many communication systems to operate within the same spectrum. RF interference has always been a concern on aircraft. Initially, aircraft radios were designed to operate in a simplex mode when the transmitter on the receiver was off. For these applications the same antenna could be used. For many applications this is still the case, but there are a growing number of applications that require full duplex operation. For these applications requiring full duplex operation, traditionally, the transmitter and the receiver use separate antennas and the transmit and receive frequencies are separated. Combining frequency separation and physical separation of the antennas reduces the possibility of interference.

The probability of interference on an aircraft has tended to increase for a variety of reasons, including higher transmitter power levels, less filtering capability in the radios to reduce cost and size, more frequency bandwidth use, spectrum crowding, and the expanding number of radios. Interference cancellation systems are becoming a part of the aircraft communication system. A popular interference cancellation design approach samples the transmitter output and then feeds this signal into the receiver out of phase with the transmitted signal (the interfering signal); and thus the potential interfering signal is cancelled. This is an oversimplification of the design but is basically how the cancellation system works.

The onboard radios are often in the same location on the aircraft, but the antennas are physically separated to aid in the interference cancellation. Therefore, the time delay of the signal to be used for cancellation has to be equal to coaxial cable runs from the radio to the transmit antenna, plus the free space distance between the transmit and receive antenna, and the coaxial cable runs back to the receiver. This delay is often accomplished by using a length of coaxial cable to equal this time delay. The cable used for the time delay is normally coiled and stowed on top of the equipment rack. For better operation in the cancellation system, lower loss cable is often used resulting in a larger coil of stowed cable. An alternate design approach could use an optical implementation, with the sample signal being converted into the optical domain to accomplish the necessary time delay and then converted to the RF domain to accomplish the signal cancellation. This again is a simplification of the design implementation.

The time delay required for interference cancellation on aircraft can range from less than 1 m up to 30 m. There are a number of optical designs and implementations that could be used to accomplish the required time delay for this application. Although the required amount of time delay can be closely approximated by measurement, there is a need to delay the signal so that the two signals are out of phase when combined. In addition, the two signals need to be equal in amplitude, and the optical technique used to accomplish the delay should not distort nor add noise to the signal. The fixed positions of the transmitting and receiving antennas reduce the implementation difficulties as in a PAA scenario. The optical delay modules could be designed to provide a time delay bank with different delay times, where the specific time delay required could then be selected to meet the need of the specific installation.

In addressing the communication system designs and time delay requirements, it is important to consider cost, power consumption, physical size, and availability of standard parts when evaluating a potential solution. While conversion from an RF to an optical domain can bring many benefits to supply a less costly and lighter solution, crossing domains also requires consideration of added distortion to the RF signal, which might result from conversion of the RF to the optical domain during the time delay of the signal, and conversion back to the RF domain. In addition, the amount of noise that might be added to the RF signal during this process has to be considered.

For a RF photonic link, RF signals would be converted to the optical domain and transported in the optical domain. The RF signal would then be recovered from the optical domain by a photodetector. For analysis purposes the characteristics of E-O conversion, optical fiber transmission, and O-E conversion in respect to the performance of the RF photonic links can be considered.

Important performance parameters of a RF photonic link are the bandwidth, RF link gain, link linear dynamic range, and noise figure. For most applications, phase linearity, group delay, and amplitude conversion to phase distortion are also concerns. An optical link is generally designed to meet stringent requirements on spectral purity to achieve good system performance. The goal of the designer of the optical link would minimize the degradation of the microwave signal by maintaining spectral purity, especially in terms of minimizing phase noise.

Intensity modulation and direct detection (IM-DD) are the common modulations in fiber systems for digital and analog applications. The transfer function of an optical fiber with a length of z (see Ref. 5) can be described as follows:

$$H_f(\omega)=C_{\text{IM-IM}}(\omega)+\frac{H_{\text{PM}}(\omega)}{2}C_{\text{PM-IM}}(\omega), \tag{1}$$

where $C_{\text{IM-IM}}(\omega)$ and $C_{\text{PM-IM}}(\omega)$ are the IM-IM and PM-IM conversion functions, respectively; $H_{\text{PM}}(\omega)$ is the (small-signal) transfer function of the relation between IM and PM for a given transmitter. Dispersion, loss, and nonlinearity of optical fibers can be reflected and analyzed using this general expression.

The dispersion and nonlinearity of fiber may, in certain scenarios, strongly enhance the conversion between the IM and the phase modulation (PM) of the optical carrier. However, if we neglect the influence of loss and nonlinearity, we get a simplified form:

$$C_{\text{IM-IM}}(\omega)=\cos\left(\frac{\beta_2\omega^2 z}{2}\right)$$

$$C_{\text{PM-IM}}(\omega)=2\sin\left(\frac{\beta_2\omega^2 z}{2}\right), \tag{2}$$

where $\beta_2=-\lambda^2 D/2\pi c$, where D is the dispersion parameter of optical fiber.

Laser diode (LD) direct modulation is a simple technique to generate a RF signal in an optical system. However, to avoid the nonlinearity of LD, external modulation with a Mach-Zehnder (M-Z) modulator, an electroabsorption (EA) modulator, or possibly a directional coupler modulator, could be used. Heterodyning is another method that could be used to generate a RF signal in an optical system. Optical heterodyning using a square-law photodetector generates a mm-wave having the frequency equal to the beat frequency between the two lightwaves. One way to minimize the phase noise contribution to the mm-wave is to insure that the phases of two lightwaves used in the heterodyning process be correlated. For this there are two approaches[6]: one is to use a V_π-biased electro-optic modulator, and the other is to use a mode lock laser diode (MLLD). Freedom from the fiber dispersion effect and full modulation depth is inherent to the MLLD scheme.

There are a number of schemes that can be used to avoid response fading of the DSB signal in fibers to mitigate the influence of dispersion and nonlinearity on the two sidebands of the modulated lightwave.[7,8] Analysis and experimentation show that the SSB signal has better performance characteristics and can pass the signal, although some ripples occur which will distort the signal and cannot be removed completely.[5,9] Optical down conversion to the RF domain is effected from low-mixing efficiencies and high-noise figures when compared to the traditional microwave mixers. There is work underway to improve the performance of this part of the optical link[10] and to improve the overall performance characteristics of the optical link.

For many applications the complex structure of the RF signal has already been generated and merely needs to be converted to the optical domain, processed as needed, and then converted back to the RF domain with the necessary time delay. An implementation of this type has been developed and is on the market.[11] It provides a fiber-optic link to replace coaxial cables for RF signals from 1 to 11 GHz. The design approach for this product provides the basic architecture for similar design, and would provide an interface between a RF system and an optics system (50 ohms for RF to 10 ohms for a laser diode). It also provides a suitable dynamic range, which will meet the requirements for a variety of RF applications, and addresses the noise figure problem, which could contaminate the RF signal.

3 Communication Satellite Simulators

Many communication satellites are designed with time as a part of access and use of the satellite. For example, communication satellite systems using frequency hopping for digital communication requires the transmitting terminal to transmit the signal so that the signal will arrive at the satellite when the receiver has been tuned to that frequency. This requires the transmitter to precorrect the timing of the transmitted signal to account for the space propagation (a precorrection in time to account for a nominal 36,000 km, for satellites in a synchronous equatorial orbit).

Some of these systems even require an acquisition of satellite timing (make adjustments in the terminal time) to account for all the system time errors: terminal time, satellite time, and estimated propagation time in the terminal.[12] These systems require comprehensive testing on the ground to thoroughly integrate the operation of the ground terminal with the satellite before the satellite is placed into orbit. A ground simulator is often maintained even after the satellite is placed into orbit to test new terminal designs.

One basic problem is how to simulate the 36,000 km propagation delay. For this application, with this much time delay, coaxial cables are not an alternative. One approach would be to digitize the transmitted signal, store the digitized signal for the required time, and then convert the signal back to RF. This approach has a number of obvious drawbacks. Another approach is to adjust the terminal timing, where it would have an error equal to the propagation time to the satellite (delay the transmitted signal). This approach is difficult, since the radio often works from a precision frequency standard; and, also, adjusting the terminal timing to compensate for the transmission delay to the satellite will not provide the time compensation for the downlink signal from the satellite to the terminal receiver.

Many simple transponder communication satellites are now using time division multiple access (TDMA) to allow multiple users to access and share the same satellite channel. This requires each terminal to accurately precorrect the timing of the transmitted signal to satellite to avoid interference with other users, and some sort of controller on the ground to act as the master time source for the ground terminals. Some of these satellites were placed into orbit before the TDMA schemes were conceived. Therefore, any new terminal designs with the TDMA need to be tested on the ground with a satellite simulator, including a technique for realistically simulating the 36,000 km time delay.

For communication systems requiring a 36,000 km time delay for testing, optical implementations are limited, but there are optical techniques that are to some extent feasible. One brutal approach is to use fiber optic cable. If we assume a conventional fiber's diameter is 250 μm, a single 24,000-km-long fiber (assume glass fiber with index 1.5) would occupy 1.2 m^3 solid physical volume with a weight of approximately 3000 kg, resulting in an impractical approach. If we consider WDM techniques, which could simultaneously transmit more than 36 channels in a single fiber, we could possibly have a reduction factor of 36. Some companies have goals with WDM techniques of up to 320 channels. The 36-channel approach would reduce the required fiber length to around 700 km and a 320-channel would reduce the required fiber length to approximately 75 km. This would still result in a very large and costly system, and although this implementation is not a desirable solution to the problem, it has the potential to be realized.

New findings[13] on the extremely dispersive devices, such as photonic bandgap[14] (PBG), or Bragg grating soliton,[15] show a potential of dispersion $>10^9$ ps/km-nm, which means 1-nm wavelength change will result in a 1-ms/km delay factor. Then, the 36,000-km time delay requirement could conceivably be reduced to approximately 120 km at 1-nm change, or 12 km at 10-nm change, though this technology still lacks maturity.

4 Optical Time Delay Techniques

There are a number of optical techniques that can be used to accomplish the time delay required in the three communications systems described before. These include fiber, waveguide, free space, micro-electro-mechanical systems (MEMS), index changing, and WDM. Major features of these optical design approaches are described in Tables 1 and 2.

Optical TTD (OTTD) has a number of advantages over the electrical implementation counterparts. The OTTD is inherently wideband and can provide instantaneous changes within the operating frequency band, is immune to electromagnetic pulse (EMP) and electromagnetic interference (EMI), and also can be designed to be compact, lightweight, and provide long life.

Theoretically, optical path is attained by $S=nL$, where n is the medium refractive index and L is the absolute (vacuum) physical distance. With $\Delta S=\Delta(nL)=L\Delta n+n\Delta L$, three possible types of time delay approaches can be identified. Among them, ΔL approach has several major characteristics, such as discrete length, mechanical adjustment, and low loss; Δn approach includes index changing and wavelength-changing induced index-changing (sometimes also associated with length variation). This approach has potentials for applications in RF frequencies at Ka-band and above to provide continuous TTD tuning; $\Delta(nL)$ approach is a hybrid scheme and has a variety of implementations, including some innovative ones. Some of the typical embodiments are:

- Dispersive components [e.g., fiber Bragg grating (FBG)] with the major advantage of reduced physical dimension (L). The inherent drawback is that the higher dispersion will adversely affect wide instantaneous bandwidth. Also, if it involves any physical length control but without lithographic-like technique, which is often the case, it will be very difficult to apply.
- Another technology approach includes acoustic liquid crystal, and Piezoelectric transducer (PZT) techniques. This technology is considered technically easier and is somewhat more mature. The drawbacks with this approach include bulky, complex design, and slow speed.
- Free space (Lissajous-pattern-multipath devices or ellipse waveguide plate) technologies could be very straightforward, but have the problems of space reuse and loss.

The various technologies described so far can be accomplished with a wide range of processes and, as a result, the specific process selected would depend on the application and requirements. For the Ku/Ka band antenna, as discussed previously, maximum delay lines are related to the size of the PAA, which, in turn, is related to wavelength; and, if partitioning is adopted in the design, the maximum delay of the various subarrays is the design consideration parameter. Waveguides, including polymeric waveguides, are considered a suitable alternative for this application, with MEMS technology also a suitable alternative but lacking in maturity.

For applications requiring long time delays, optical fiber is the most viable alternative. Waveguides, silicon or polymer, on the other hand, can achieve very high precision, $<1\ \mu$m, though the integration with other components may compromise this advantage significantly. Experiments show that an individual fiber cut could be within 1 mm, while the achievable system level accuracy will be around 5 mm.[16]

For applications requiring continuous time delay variations, direct index tuning and wavelength tuning with dispersion light paths are two good candidates. The two implementations include tunable delay line (TDL) units and TTD line banks. While the former approach provides a discrete and large delay time adjustment, the latter provides continuous delay time tuning.

In general, optical technologies can be used to accomplish time delay or time delay tuning. A number of technologies have been discussed and the following are considered core optical TTD technologies:

1. Dispersive waveguide (including FBG) which is a mature technology and can provide approximately $100\sim1000$ ps/nm-km.
2. Polymeric based index-tuning materials that will provide ~1 ps controllable time delays for use with Ka-band and above frequency applications. This technology also has potential applications at much higher operating frequencies (>100 GHz), including monolithic integration with high-speed devices.[17]
3. The MEMS technologies will provide a capability from 10 μm to >1 cm/per translational step (corresponding to time delays ranging from 30 fs to 30 ps), which is independent of wavelength. The feature will provide an opportunity for integration (such as VCSELs) and programmable time delay subsystems.

5 Conclusions

Optical designs offer a wide range of techniques that can be used in communication systems to provide the necessary time delays where required. There is a wide range of variations in the implementations of these optical techniques. In addition, the technological advances are continuing for all these techniques and some very promising optical techniques are continuing to mature. The use of dispersive waveguide, polymeric based index-tuning materials and MEMS technologies can provide an optical design solution for many applications requiring time delay.

There is a broad range of development opportunities related to the integration of photonic time delays into communications systems. Technologies need to be improved to minimize the distortion of the RF signal as a result of conversion to the photonics domain, processing through the optical time delay scheme, and conversion back to the RF domain, including adding noise to the RF signal during this overall process. Packaging and interfaces compatible with communication systems also need to be developed. Finally, the costs of these optical alternatives to accomplish time delay need to be competitive with other approaches, and/or provide a significant advantage over the traditional approaches.

Table 1 Optical true time delay technologies review ("mechanical" independent parameter, ΔL).

Media	Variations	Advantages	Disadvantages	Notes
Fiber	Glass	*Straight-forward	*Bulky	Large amount of delay lines will pronounce the bulky problem.
		*SM lowest loss(0.2 dB/km)	*Hard to handle	
		*Compatible with other components (systematic view)	*Compatibility with switching network (polarization-sensitive and large amount of)	Higher band, the precision will become constraint factor (10 ps$\sim$3 G@10°).
			*Delay precision $\sim$1 mm ($\sim$5 ps)	
	Plastic (POF)	*Cheap	*Not in mainstream	
		*Safe and easy to handle	*SM not available	
		*Relieved bend radius	*Harsh environment	
			*Poor splicing capability	
Waveguide	Conventional silica-based PLC-WG	*Photolithography defined precision *Potential integration, or, compact packaging	*Expensive fabrication facilities *Long turnaround multictep procedure *Complicated pattern layout	Silica-based WG 1–7 dB/m, max. $\sim$10 m Layout problem will not be a serious issue when entering into volume production stage.
(Compact and component integration)	Polymer-based WG	*Potential integrated with polymeric EO/TO device	*Material availability	Though potential 150 m/ 5″ wafter surface $\sim$10 dB/1 m prevent it from applications requiring longer length Lithography precision easy to achieve 1 μm, potential suitable up to 1 THz application
		*multilayer possibility	*Stability, repeatability	
		*Printable patterns	*Overall technique maturity	
		*Low index, high speed	*Supposed to be cheap (not yet)	
		*Simple process		Amplifier polymers in R&D.
MEMS (potential "tunable")	Surface and bulk	*Incremental steps *Wavelength independent *Integration potential *Programmable *Flexible and compact	*Expensive *Long time and low yield so far *Lossy	Crystal orientation (100) and (110) forms 45° mirror with evaporated aluminum. Single tranaslational step could be $>$6 mm (20 ps)×2 (a dynamically changing area and the potentials are great).
Free space	Various types	Vary	Typically bulky	

Table 2 Optical true time delay technologies Review (possible controlled continuum of delays, Δn).

Schemes	Variations	Advantages	Disadvantages	Notes
Direct index change through E or T	Electro-optic effect	*Fast speed $<$ns (limited by circuit structure for polymer)	*Δn is small	Polymer materials coefficient: 100 pm/v
			*High driving voltage	$\rightarrow 10^{-4}$ /MV/m (Δn)
			*Poling and long term stability	$\rightarrow$1 m$\sim$100 um$\sim$0.5 ps
	Thermo-optic effect	*Δn is larger that EO	*Speed is slower than EO ($\sim$ms)	10^{-4}/°C(Δn)$\rightarrow$5 ps/10°
			*Long term stability	silica 10^{-5}/°C(Δn)
WDM	(Fiber, grating)	*Much larger effective ΔS change by changing λ	*Fast tunable/(multiple) lasers, filters ($\sim$10 ns) required	Long term environment and hardware imperfections
Media index is dependent on λ, $\Delta\lambda \rightarrow \Delta n$		*In the mainstream of telecom. technology	*FOM is not high enough (e.g., 100 ps/nm-km) compared to laser technique *Potential conflict with extremely high instantaneous bandwidth *Dispersion linearity	Complicated but doable, many research efforts have been directed to

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