

AEROSPACE INFORMATION REPORT

SAE AIR5601

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A Guideline for Application of RF Photonics to Aerospace Platforms

FOREWORD

This document was developed by the SAE AS-3A-2 RF/Analog Technology Task Group under AS-3 Fiber Optics and Applied Photonics and AS-3A Applications. The formation of this task group was approved at the fall meeting of the SAE AS-3 committee in October 2002. While RF photonics technology can potentially provide enormous benefits to future aerospace platforms, the technology is significantly different from conventional RF technology and requires engineers to think in somewhat new terms and adapt to the peculiarities of the medium. Establishment of guidelines for the application of RF photonics technology will assist avionics systems suppliers and customers in the design, development, and testing of future systems which incorporate photonics networks that include analog RF signal transmission. This document is dedicated to that goal. There are many contributors to be recognized for their efforts in developing this document and the AS-3 Fiber Optics and Applied Photonics Committee is grateful for everyone's contributions. Unfortunately we cannot list the names of individuals in this document.

The intended audience for this work is new engineering graduates, experienced engineers who are new to fiber optics and managers who are new to fiber optics or have been away from day-to-day exposure to fiber optics for a while. Realizing that the SAE is an international organization and that information published by the SAE is available worldwide, the information contained herein is limited to that which is also available independently from the various companies which provided it. This document only serves to gather and collate the information from the many various sources to facilitate the understanding and utilization of RF/Analog signals transmitted over fiber-optic networks.

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This task group was formed with an open invitation to professionals in government and at major platform developers and suppliers of photonics systems and components. Beginning with a few contacts from SAE and existing programs, the call went out: who do you know with RF photonics expertise? From these new contacts: who do you know? So I call this task group the "who do you know, who do you know group". These are professionals known by their peers as experts in the field of RF photonics technology. They have worked on a volunteer basis with the support of their company or organization to develop a document that defines the current art of RF photonics. I am indebted to them and their organizations for their dedication to this effort.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) is devoted to the challenges of applying optics to new advanced RF analog systems only; digital data link applications are covered elsewhere in protocol/architecture specific documents like Fibre Channel, ATM, Ethernet, Sonet, etc.

This document has four main goals:

1. To completely cover today's capabilities and limitations of fiber in meeting multiple types of advanced RF system requirements.
2. To discuss near term advancements being developed that will bring us closer to meeting all the capabilities of current copper coax systems.
3. To identify the benefits of fiber optics for RF systems
4. To identify challenges for future development.

2. REFERENCES:

2.1 List of Acronyms:

ACFT	aircraft
A-CPS	asymmetric co-planar strip
A/D	analog-to-digital
ADC	analog-to-digital converter
AIR	Aerospace Information Report
AM-VSB	amplitude modulation - vestigial side band
APC	angle-polished connector
APD	avalanche photodiode
AR	anti-reflective
ASK	amplitude shift keying
ASL	asymmetric strip line

2.1 (Continued):

AWG	arrayed waveguide grating
BIT	Built-In Test
BM/B	blind-mate/backplane
CATV	cable television
CDR	compression dynamic range
CDR	critical design review
CET	(section 8.6.19)
CFE	contractor furnished equipment
CNR	carrier-to-noise ratio
COTS	commercial off the shelf
CPS	co-planar strip
CPW	co-planar waveguide
CW	continuous wave
CWDM	coarse wavelength division multiplex
DARPA	Defense Advanced Research Projects Agency
dB	decibels
dBc	decibels relative to carrier
DC	direct current
DFB	distributed feedback
DIP	dual inline package
DR	dynamic range
DT/OT	(section 8.6.7)

2.1 (Continued):

DWDM	dense wavelength division multiplex
EA	electro-absorption
EAM	electro-absorption modulator
EB	expanded beam
EDFA	erbium-doped fiber amplifier
EDWA	erbium-doped waveguide amplifier
EIA	Electronic Industries Alliance
EMI	electromagnetic interference
EML	electro-absorption modulated laser
EO	electro-optic
ESS	environmental stress screening
FIR	finite impulse response
FKE	Franz-Keldysh effect
FM	frequency modulation
FMECA	failure modes, effects, and criticality analysis
FON	fiber optic network
FP	Fabry-Perot
FRACAS	failure reporting, analysis and corrective action system
FSK	frequency shift keying
FWHM	full-width half-maximum
G	gain
GHz	gigahertz

2.1 (Continued):

HAZMAT	hazardous material
HF	high frequency
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
IF	intermediate frequency
IM	intermodulation
IM	intensity modulation
IMDD	intensity-modulation direct-detection
I/O	input/output
IPA	isopropyl alcohol
IPT	integrated product team
kHz	kilohertz
LAN	local area network
LED	light emitting diode
LNA	low-noise amplifier
LO	local oscillator
M	maintainability
M-DEMO	maintainability demonstration
MEM	micro-electro-mechanical
MEMS	micro-electro-mechanical systems
MFD	mode field diameter
MHz	megahertz

2.1 (Continued):

MMF	multimode fiber
MMI	multimode interference
MMIC	monolithic microwave integrated circuit
MQW	multiple-quantum-well
MZ	Mach-Zehnder
MZI	Mach-Zehnder interferometric
MZM	Mach-Zehnder modulator
NALL	naval aviation lessons learned
NDI	nondevelopmental item
NF	noise figure
OA	optical amplifier
OA	(section 8.6.7)
OEO	optical-to-electrical-to-optical
OOK	on-off keying
OPEVAL	(section 8.6.20)
OSA	optical spectrum analyzer
OTDR	optical time division reflectometer
PC	physical contact
PDR	preliminary design review
PIN	p-type, intrinsic, n-type
PM	polarization maintaining
PSK	phase shift keying

2.1 (Continued):

QAM	quadrature amplitude modulation
QCSE	quantum-confined Stark effect
QW	quantum well
R	reliability
RC	resistor-capacitor
RDT	reliability development test
RF	radio frequency
RIN	relative intensity noise
RMRB	reliability and maintainability review board
SAE	Society of Automotive Engineers
SCM	subcarrier multiplex
SEE	single electron effect
SFDR	spur-free dynamic range
SLD	super-luminescent diode
SMF	single-mode fiber
SOA	semiconductor optical amplifier
SRA	system replaceable assembly
SSMF	standard single-mode fiber
SWP	size-weight-power
TE	transverse electric
TEC	thermoelectric cooler
TECHEVAL	(section 8.6.20)

2.1 (Continued):

TIA	transimpedance amplifier
TIA	Telecommunications Industry Association
TID	total ionizing dose
TM	transverse magnetic
TWEAM	traveling-wave electro-absorption modulator
UHF	ultra high frequency
US	United States
VCSEL	vertical-cavity semiconductor laser
VFL	visual fault locator
VHF	very high frequency
WDM	wavelength division multiplex
WRA	(section 8.6.15)
WWII	World War Two

3. RF PHOTONICS AEROSPACE APPLICATIONS AND ADVANTAGES:

In this section, examples of some typical applications of RF Photonics are given to illustrate the unique properties of the technology and how they might be applied to a range of systems. In most cases, the applications are real (in the sense that similar systems are already in operation). The examples have in common that they use optical components for signal transport, sometimes including signal replication and RF delay, since, as stated in the Foreword, that is the current state of the art. They typically present very demanding bandwidth, sensitivity, and dynamic range requirements. Additional examples are from signal distribution applications, since they exhibit many of the advantages for long-distance transmission of broadband signals with extreme amplitude flatness and low dispersion. In this latter area are towed decoys, delay lines, and radar test simulators. Applications to communications and radar systems are less common because their typically very high dynamic ranges (over relatively narrow instantaneous bandwidths) generally exceed the current capabilities of optical components.

3. (Continued):

It is useful here to summarize at this point the general advantages, or rather unique characteristics of, optical link components compared to conventional coaxial cable-based RF designs. For reference, a high-level functional block diagram of one form of the modulation process is given below in Figure 1. A full treatment of other modulation methods and the associated components is given later in the document in Section 6 on Link Components.

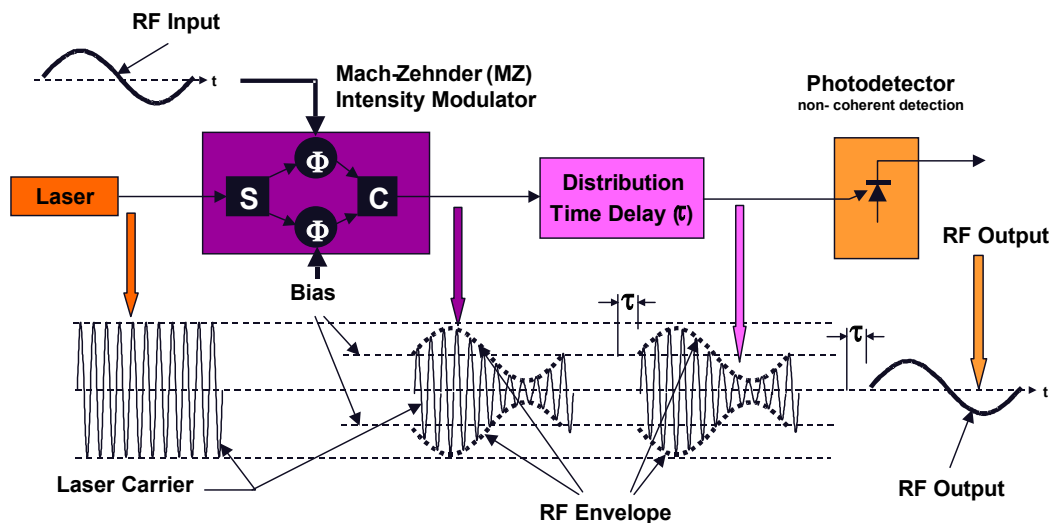


FIGURE 1 - Overview of Basic Modulation Process

3.1 Advantages of Photonics in RF Systems:

- 3.1.1 Electromagnetic Interference (EMI) Resistance: A common problem in RF design is preventing electrical interference coupling onto a signal pathway from adjacent signal paths or power supply lines or the external environment. Such coupling can create exasperating anomalies in the performance of the systems, and can be very hard to diagnose and cure. The problem is normally handled by careful attention to grounding, use of EMI gaskets on the RF enclosures, shielded coaxial cable, and physical separation from potentially offending lines.

Fiber-based systems have much less susceptibility to such coupling. The RF enclosures at each end of the signal pathway still require the same degree of attention to EMI, but the signal pathways are effectively totally immune. This is due to the fact that they are made of silica glass (a non-conductor), and therefore they neither produce, nor respond to, external electromagnetic fields. This is a major advantage in system design, integration and test.

- 3.1.2 Superior Phase Stability: Many multi-channel receiver systems and some signal distribution applications require maintenance of phase coherence of the RF signals in multiple paths. This phase-coherence is affected by many environmental factors, most notably temperature, which causes the cable characteristics to change. While not immune to such effects, the rate of change of phase with temperature of optical fiber is on the order of one tenth that of coaxial cable.
- 3.1.3 Extremely Low Optical Transmission Loss Leading to Platform Independence: Once an RF signal has been modulated onto an optical carrier, the losses it experiences transiting in the fiber are orders of magnitude less than those in coaxial cable. Instead of a typical loss of 0.3 dB per meter in coaxial cable, losses in fiber can be as low as 0.1 dB per kilometer. This allows extreme freedom in the location of antennas (or other signal sources) and receivers, and in the fiber routing within platforms. It could be argued that it makes the system completely independent of the platform, in that the system can be rehosted, say from an aircraft to a ship, with essentially no consideration of the distances between the system elements. This is decidedly not the case with conventionally implemented systems. Such low transmission loss also presents opportunities in its own right. RF delay lines are an example, where the path is intentionally extended.
- 3.1.4 Small Size/Light Weight Cabling: Optical wavelengths inherently require small diameter waveguides, which is what optical fiber is. Unjacketed single-mode fiber, the most suitable medium for RF transmission, is as thin as a human hair, and just as light. Even with physical jacketing or shielding appropriate for aircraft use, the size and weight seldom exceeds that of a single twisted-pair of copper conductors. However, the fiber has immensely greater bandwidth than the twisted copper pair.
- Fiber also tolerates tighter bend radii before suffering signal degradation. Instead of a nominal two-inch bend radius as required for 0.141-inch coaxial cable, standard telecommunications fiber can be used with a one-inch bend radius, and specialty fibers can work down to a one half-inch radius. This property eliminates many constraints normally present in the cable harness designs for aircraft.
- 3.1.5 Extremely Wide Bandwidth: Light energy can propagate efficiently in optical fiber over several hundreds of nanometers of wavelength (780 to 1650 nm). This equates to many Terahertz of bandwidth. The advantages of this property in RF system design are that there is no gain slope due to single-mode fiber transmission as there is with coaxial cable, nor is there any appreciable dispersion (variation in group-delay), since any RF signal occupies an extremely small fractional bandwidth of an optical carrier. This makes fiber ideal for transmission of millimeter-wave RF or very short pulses of RF. These statements remain true even when multiple RF signals are multiplexed onto the same fiber.

- 3.1.6 Growth Capability and Scalability: Inherent in the wide bandwidth property is a tremendous growth capability and scalability as system requirements evolve. As the RF frequency of the link increases or decreases, typically only the RF components at each end of the fiber pathway need to be changed, certainly not the fiber run itself. If additional parallel signal paths are required, they can re-use the existing fiber pathways by wavelength division multiplexing, where additional optical carriers are coupled into the same fiber, then separated prior to RF detection by optical filters. This can usually be done with very little effect on the original, single link performance. Such an arrangement can also serve as the basis for switching, albeit with some RF performance degradations.
- 3.1.7 Survivability and Vulnerability: The ability to route signal pathways almost arbitrarily and to replicate the signals by splitting the optical power into multiple fibers provides significant opportunities to enhance the survivability and vulnerability characteristics of the system. Individual pathways can be routed away from likely damage locations, immediately reducing the likelihood of system disruption. Assuming sufficient optical power is available, signal pathways can also easily be duplicated (after modulation) simply by splitting the optical power among multiple fibers. The redundant fibers can then each be routed through different parts of the aircraft, greatly reducing the chance of all of them suffering damage. At the receiver end of the optical link, any one of the surviving paths could be selected to complete the link.
- 3.2 Signal Distribution and Delay Applications:
- 3.2.1 Antenna Remoting and Signal Distribution: The first example of an application of fiber optics is that of antenna remoting. In this application, a fiber-optic path replaces the traditional coaxial cable or rigid waveguide for connecting an antenna to a receiver. The basic situation is shown in Figure 2 below.

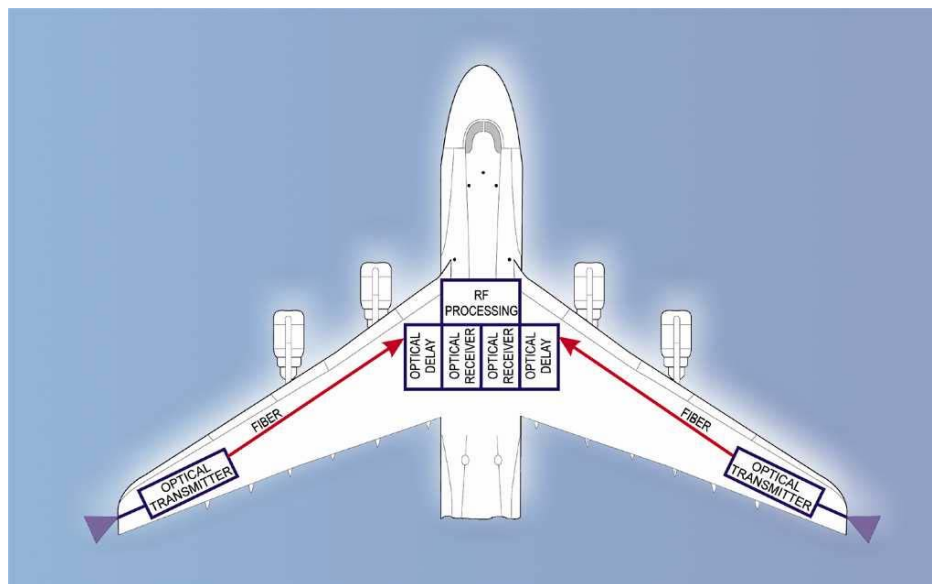


FIGURE 2 - Typical Configuration Showing Centralized RF Processing

3.2.1 (Continued):

Transporting inputs to their respective receivers while maintaining flatness of gain and group delay, high dynamic range, and performance over temperature and vibration requires at the least very careful design. In some cases, expensive and complicated RF processing at the apertures is required to condition the signal prior to transport. Examples of this include preamplification, equalization, pathway calibration, and in the most demanding cases, downconversion. Fiber all but eliminates these considerations.

Another common application is the distribution of internally generated RF signals to remote locations. Examples of this are distribution of a local oscillator signal to multiple downconverters, distribution of test or calibration signals to aperture electronics, or transmission of the output of a signal generator or exciter to power amplifiers for subsequent free-space transmission. Through the use of optical splitters, multiple copies of the signal can be sent to different locations. With care, phase coherence of the signals can be maintained.

The most prevalent examples of the latter usage are the various fiber-optic towed-decoy countermeasure systems being deployed on military aircraft. A typical configuration for such devices is shown below in Figure 3.

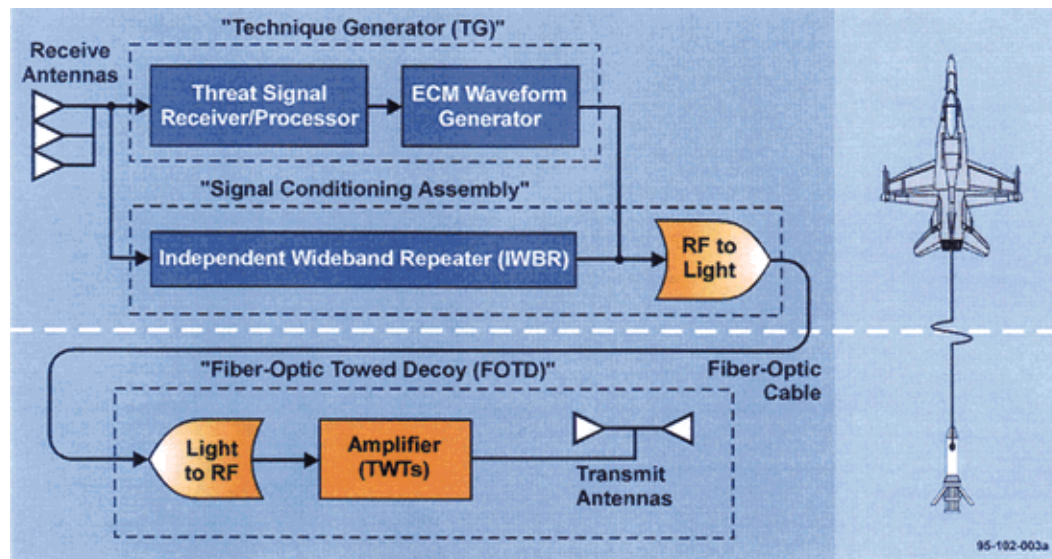


FIGURE 3 - Typical Fiber-Optic Towed Decoy Configuration

3.2.2 RF Delay Lines: Broadband fiber-optic RF delay lines really are simply RF photonic links that have the fiber path artificially extended to delay the signal by prescribed amounts. Typically, the excess fiber is spooled in close proximity to the other RF and optical components to make a compact and rugged self-contained assembly. An example of a multi-channel version of such an assembly is shown below in FIGURE . Important things to note about these applications are that the physical lengths of the fibers can be trimmed to set the delay to within approximately 50 psec of the desired amount, using a process that is much easier than the trimming of coaxial cables. These trimmed fibers can be augmented by electrically or manually controlled broadband optical delay adjusters to achieve a delay accuracy of better than 0.1 psec. Also, note that all the inherent properties of fiber-optic transmission apply to their use as delay lines. The RF-photonic delay lines would work as well at 40 GHz as at 40 MHz (subject to proper selection of the RF components involved in the design). There is negligible dispersion in the delay line, much-reduced amplitude ripple or slope, and insignificant triple-transit issues compared to some other delay approaches. Delays up to a hundred microseconds or more have been achieved, although not necessarily in a package as small as that shown in Figure 4. (For design purposes, the speed of light in a fiber is approximately 0.7c.)

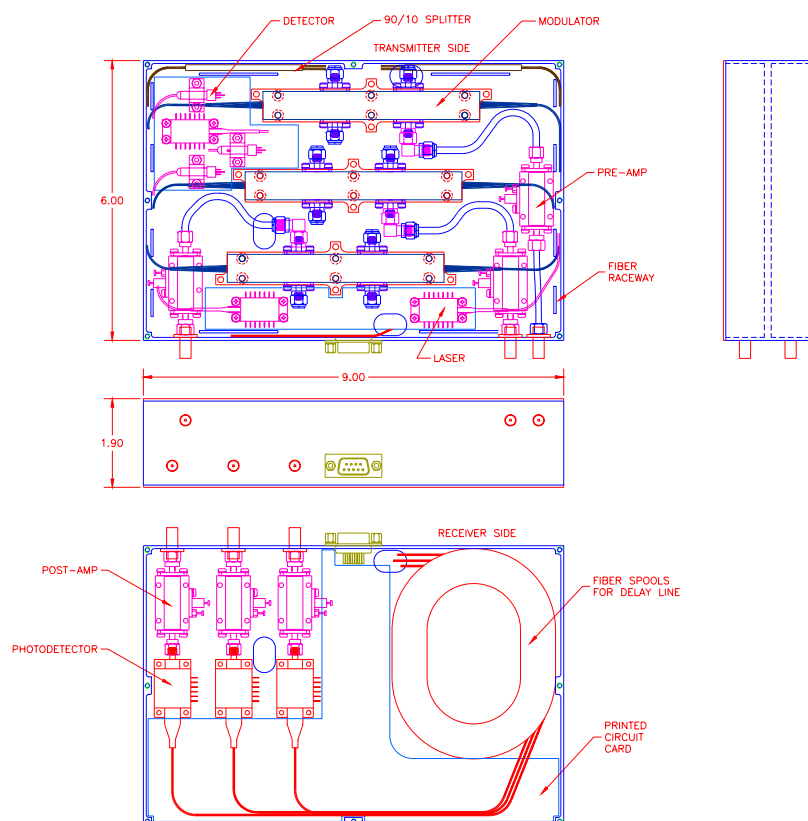


FIGURE 4 - Schematic of Multi-Channel Fiber-Optic Delay Line

3.2.2 (Continued):

It is obviously also possible to embed such delays within antenna remoting applications. In this case, the fiber spool is the only additional required element, and is totally passive. In a sense, the delay comes “for free”. An example of this architecture is shown in Figure 5 below. This particular diagram depicts a system that has been operational on a military platform since 1998. Note that it also uses splitters within the receiver to replicate the signals prior to imposing prescribed delays on each signal path. This can be done easily in a fiber-optic system as long as there is adequate optical power available in each path to maintain the link’s dynamic range. This is not a particularly stringent demand with only a two-way split. It is important to remember that the insertion of such passive optical components such as fiber lengths and splitters into a link, if done properly, does not affect its RF bandwidth, flatness, group delay, or phase coherence. This is hardly the case with conventional RF devices.

The system in Figure 5 is an example of a cued receiver architecture. Such architectures typically have a wide-band acquisition channel to quickly screen signals. For signals of interest, they then use the copy of the signal in the delayed path for finer analysis.

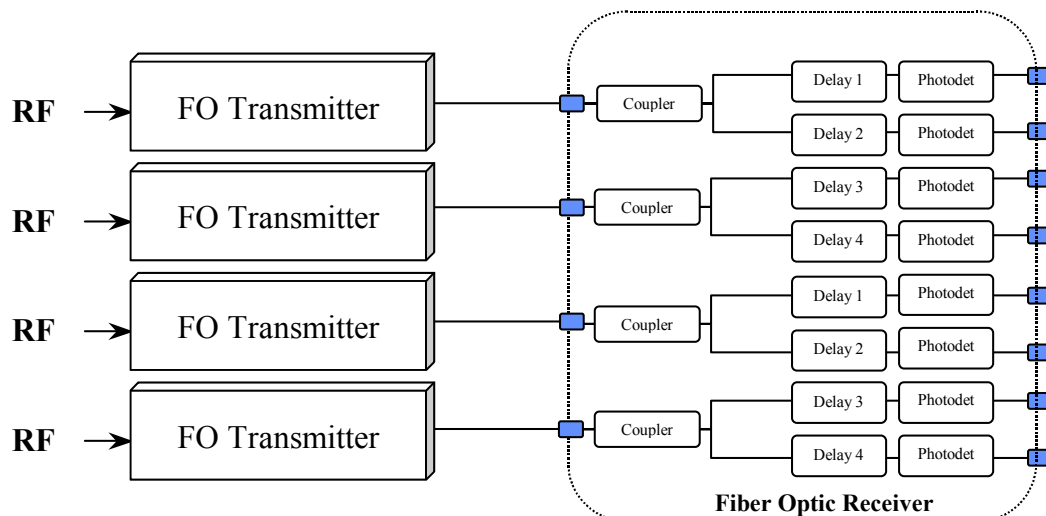


FIGURE 5 - Four-channel Fiber-optic Network with Signal Replication and Delays

- 3.2.3 Use of RF Delay Lines for Radar Testing or False Target Generation: We have already discussed how fiber-optic links, optical delay lines, and splitters can “copy” and distribute RF signals to various locations. When used in a radar test set or a radar countermeasures system, the delay function is equivalent to placing the radar return at a given range. In most cases, the radar’s actual emissions are captured as the source of the false targets. This ensures that signal processing within the radar will not reject or overly attenuate the generated returns. Adding splitters to the delays, and making the delays selectable, is equivalent to presenting the radar with multiple false targets at various ranges. All of these ideas have been exploited in various combinations to produce test equipment for radars in aircraft and to produce radar counter-measures sources. The extremely high fidelity of the optically generated copies of the radar’s emissions makes them potentially effective even against sophisticated synthetic aperture radars.
- 3.2.4 Use of Wavelength Division Multiplexing to Replace RF Switching: The basic link topology illustrated above in Figures 1, 2, 3, and 5 is referred to as a point-to-point link. One modulated optical frequency is sent down a dedicated fiber to a photodetector. It is possible, and indeed quite common in the telecommunications industry, to take advantage of the very wide bandwidth of the fiber and the other passive optical components in the link by coupling many (up to 80 at present) such modulated carriers into the same fiber for transport, then separating them at the receiver end with optical filters prior to individual detection of the signals. This process is referred to as wavelength division multiplexing (WDM), and is often done in commercial applications primarily to get maximal benefit out of existing fiber pathways. While aerospace avionics applications are only beginning to exploit the high bandwidth capability of the fiber, WDM technology does lend itself to new architectures which provide many benefits (such as redundancy without additional fiber or in-flight reconfigurability in response to failures). However, the technique becomes much more interesting to RF design when tunable, rather than fixed, optical filters are used at the receiving end to demultiplex the optical carriers. Such a configuration can be used to replace complex RF switches. The basic architecture is shown below in Figure 6.

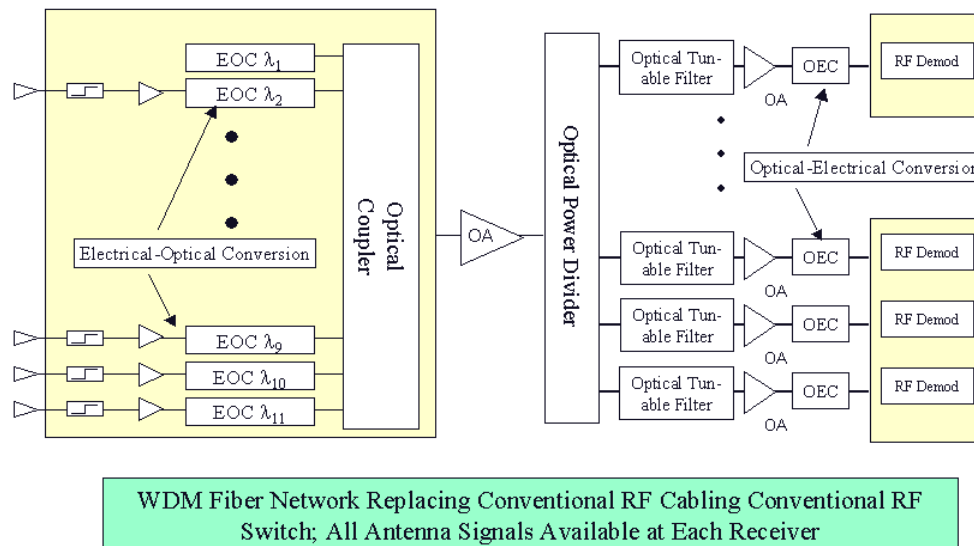


FIGURE 6 - Basic WDM Architecture Used as a RF Switch

3.2.4 (Continued):

The operation of such a switching and distribution network is based on the fact that every antenna (in this example) output is given its own optical carrier frequency (i.e., wavelength), and all of those output signals are multiplexed onto the same optical fiber. Thus, all antenna outputs are available simultaneously to every one of the receivers, i.e., it is a fully non-blocking architecture. There are several advantages of this RF-photonics approach compared to approaches based on conventional RF switches. These advantages can be especially significant in the implementation of large systems. First, the combiner (the wavelength-division multiplexer) has a fixed insertion loss (approximately 6 to 10 dB of electrical loss) regardless of the number of RF inputs (i.e., optical wavelengths) combined. In contrast, typical electrical switches have a loss of at least $(3 \times \log_2 N)$ dB if they are non-blocking. Second, a single optical splitter handles all of the separate RF input (e.g., antenna output) signals. In contrast, electrical switch networks require N separate $1 \times M$ splitters, with one splitter for each RF input signal. The optical amplifier typically present in the path likewise has a very wide (TeraHertz) bandwidth. Thus, the optical amplifier amplifies all of the RF signals simultaneously and serves to overcome the loss of splitting the antenna outputs among the receivers as well as any additional insertion loss from components such as the combiner or the tunable optical filter. Multiple amplifiers would be needed in electrical switch approaches, with those amplifiers typically being located at the antenna outputs and/or at the receivers.

3.2.4 (Continued):

It should be noted that it is not necessary for all of the combining, amplification and splitting functions to be done in a single stage. These functions can be distributed within the RF-photonic switch network to reduce the number of individual optical frequencies needed. An example of such a staged design is shown in Figure 7 below. In this case, 80 RF inputs are carried on 4 optical fibers to each of the M receivers. At each receiver location, a 1 x 4 optical switch selects a group of 20 RF inputs, after which an optical filter selects one of the 20 wavelengths for detection. This architecture can be used in large systems to allow wider frequency spacing of the optical carriers to improve channel-to-channel isolation (e.g., by reusing the same 20 frequencies four times instead of using 80 frequencies, which must be spaced more closely together). Isolation of 60 to 80 dB, electrical, can be achieved with available frequency (wavelength) multiplexing and tunable-filter components. Note that M determines the required amplifier gain for each signal. Thus, this architecture also lessens the maximum optical power required from each of the optical amplifiers, which now provide gain for a smaller number of input signals. An implicit advantage of the RF-photonic switch approach is that the reverse isolation of the switch is essentially perfect. Any reverse electrical RF signal from a receiver would need to go back through a photodetector and be modulated by that photodetector onto a lightwave signal to propagate through the other optical components to another photodetector that is connected to a separate receiver.

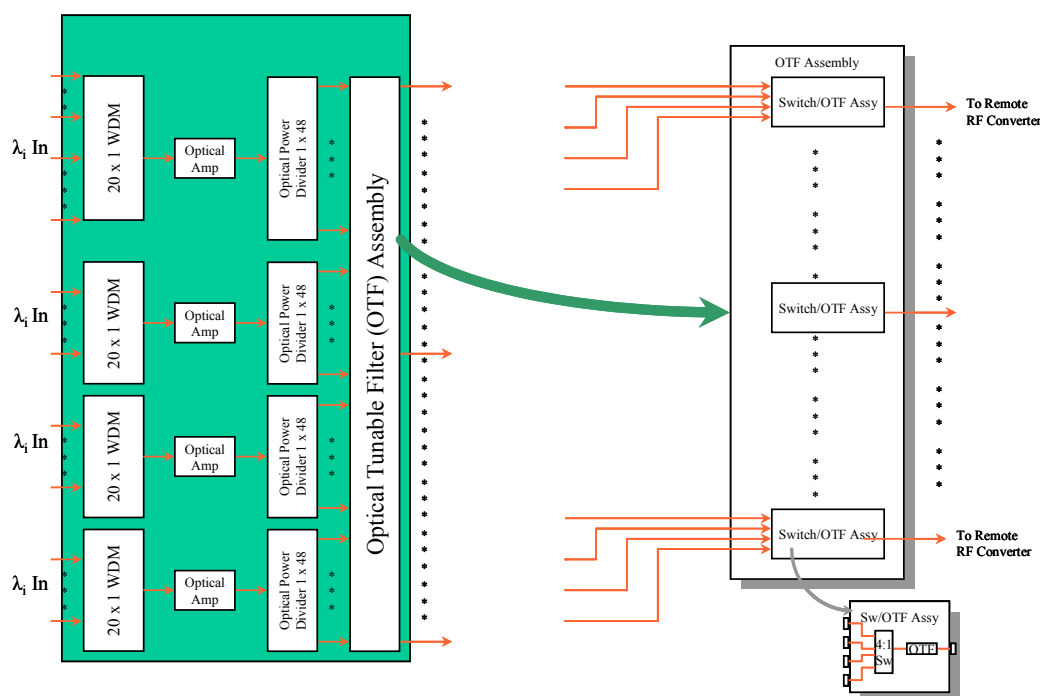


FIGURE 7 - Staged WDM Network Configuration

- 3.2.5 True Time Delay Beamforming: Optical fiber is an ideal medium in which to realize RF delay lines (as was discussed in 3.2.2), especially in phased-array antenna applications in which optical fiber links are employed to deliver RF signals to and/or from the individual antenna elements or subarrays of these elements (as was discussed in 3.2.1). To steer the “beam” - the direction in which the array transmits and/or from which it receives RF signals - requires a means of varying the delay incurred by RF signals between the common point (i.e., the single transmitter or receiver) and the individual elements or subarrays. For example, to point the beam in the “broadside” direction (i.e., along a line normal to the plane of the array) requires that an identical delay be applied to the signals addressing each antenna element, whereas to point in any another direction requires that greater delays be applied to some elements and smaller ones to others.

When deciding upon a means of adjusting the RF delays so that the array’s transmit and/or receive beam direction can be quickly steered, it might seem an obvious choice to use a network of fiber-optic switches. However, this technique typically has one or more disadvantages, in that the fastest optical switches often have higher insertion loss and/or higher cost than slower switches such as those based on MEMS technology. This loss vs. speed trade-off, combined with the desire to form multiple beams simultaneously, has led many researchers to investigate beamforming techniques that do not require optical switches. Examples include architectures that instead rely on electronic switching technologies and/or allow the delay to be determined by tuning the wavelength of the light in order to exploit the telecommunications industry’s development of tunable-wavelength lasers to enable dense wavelength-division multiplexing.

A survey of the various optical techniques for achieving true time delay beamforming would require a long chapter in a book, or even an entire book for a thorough treatment of the topic. Even a list of references that touches on all the important issues would be quite long; however, many of the most relevant papers on this topic have already been compiled into one book [1]. These papers, and others to which they in turn refer, can supply a more complete view of this wide-ranging topic than what can be provided here.

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3.3 Signal Processing and Generation Applications:

- 3.3.1 RF Signal Generation Using Photonic Processes: The photodetector is a "square law" device in that the electrical current it produces is proportional to the intensity of the light coupled into it. This process is shown pictorially and mathematically in Figure 8. If the light contains electric-field components at several optical frequencies, the optical intensity involves a squaring of the combination of those components. The photocurrent thus contains components at sum and difference values of those various optical frequencies. Lasers can be made that produce spectrally pure, single-frequency optical outputs. A RF signal can be produced at the output of a photodetector by supplying to it light from two different lasers that emit at slightly different optical frequencies. (A RF-photonic link of this type is often referred to as an optical-heterodyned link). Choosing this difference to be some desired frequency, such as 10 GHz, or better yet making the lasers' wavelength tunable, makes such a link a potential local oscillator source for frequency conversion. This RF-photonic approach is especially attractive because it can generate signals of very high frequency (e.g., millimeter wave) that is limited only by the bandwidth of the photodetector in the link.

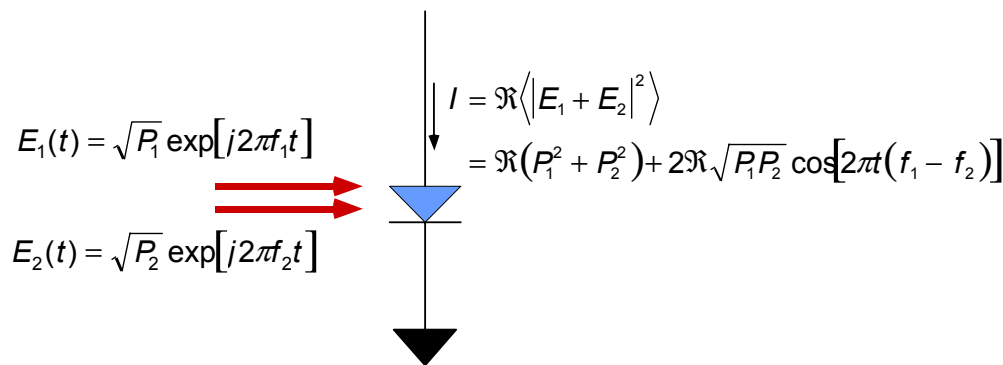


FIGURE 8 - Photonic Heterodyning Within a Photodetector to Produce RF Tones

A LO signal that has low phase noise is obtained by designing the two lasers to have small inherent linewidth and by controlling the frequency drift of one laser relative to the other. One way to phase correlate the two lasers is to optically inject RF-modulated light that is supplied by yet another laser, as illustrated below in Figure 9c. One laser is optical-injection locked to one of the modulation sidebands and the other laser is locked to another modulation sideband. [1] The modulation sidebands of this RF-modulated light are phase-correlated with each other and, thus, the two optical-injection locked lasers acquire this same phase correlation. Photonic signal generation has demonstrated phase noise less than -140 dBc/Hz for offsets greater than 10 kHz of the 10 GHz RF signal generated thereby. Certain laser configurations such as actively mode-locked lasers can produce a large number of strong, high-order-modulation sidebands from a single RF reference. Thus, the dual phase-correlated lasers can potentially generate high-stability LO signals to frequencies of 94 GHz or higher. [2] These optically generated RF tones can be transported to remote locations by placing the photodetector remotely from the lasers.

- 3.3.2 RF-Photonic Methods for Frequency Conversion: As stated earlier, a RF-photonic link can be used to distribute local-oscillator (LO) signals. Such links have the low phase noise that is suitable even for many military sensor applications. If the LO signal is amplified before being modulated onto the optical carrier, the close-in residual phase-noise typically is dominated by the $1/f$ noise of the electronic amplifier. [3] An intrinsic phase noise below -145 dBc/Hz at 10 kHz offset from the X-band signal was measured for a RF-photonic link that does not have any electronic amplifier. [4]

Instead of carrying the LO signal to electronic frequency converters (as illustrated in Figure 9a), the RF-photonic link itself can perform the frequency conversion. One way to achieve this is by cascading a pair of optical modulators in the link (as illustrated in Figure 9b). [5] The LO signal is modulated onto the optical carrier by one modulator of the cascade. The RF signal is modulated onto the optical carrier by the other modulator of the cascade. We make use of the non-linear electrical-to-optical transfer function of the modulator to achieve mixing of the LO and RF signals. As an example, the modulated optical output of a cascade of Mach-Zehnder (MZ) optical intensity modulators is described by:

$$I_{OUT} = \frac{I_{IN}}{2L_{MOD}}(1 + m\sin\omega_{RF}t) \quad \text{with} \quad I_{IN} = I_0 [1 + M\cos(\omega_{LO}t + \phi)], \quad (\text{Eq. 1})$$

wherein I_{OUT} is the intensity of the optical output from the second MZ modulator that is modulated by the RF tone of frequency ω_{RF} , and I_{IN} is the intensity of the optical output from the first MZ modulator (optical input to the second MZ modulator) that is modulated by the LO tone of frequency ω_{LO} . The electrical current produced by the photodetector at the end of the link is described by:

$$i_d = \frac{\alpha I_0}{2L_{MOD}} \left\{ 1 + \underbrace{m \sin(\omega_{RF}t)}_{\text{RF term}} + \underbrace{M \cos(\omega_{LO}t + \phi)}_{\text{LO term}} \pm \frac{1}{2} mM \sin[(\omega_{LO} \pm \omega_{RF})t + \phi] \right\} \quad (\text{Eq. 2})$$

RF term
LO term
Mixing (IF) terms

This current has components at the sum and difference frequencies of the RF and LO signals. The efficiency of the frequency conversion process depends on the modulation efficiencies (m and M) of the two optical modulators, the intensity I_0 of the light supplied by the laser, the optical-to-RF transduction efficiency α of the photodetector and the insertion loss L_{MOD} of the link. The methods to be discussed later for achieving high RF-photonic link gain also can achieve high frequency-conversion efficiency.

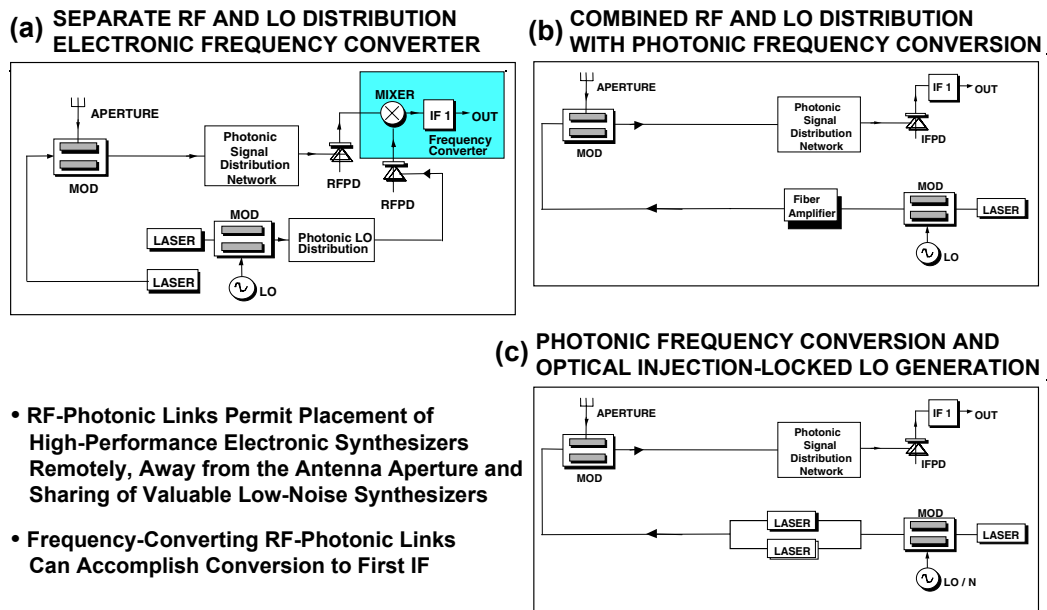


FIGURE 9 - Illustration of three approaches for accomplishing frequency conversion with RF-photonic links: (a) electronic conversion, (b) dual-modulator link, (c) optical-heterodyned link

3.3.2 (Continued)

Frequency conversion also can be accomplished by supplying the optically combined output of the dual phase-correlated lasers to another optical modulator that is modulated by the RF signal, as illustrated in Figure 9c. The two laser lines are modulated by the RF signal and produce, at the photodetector, the sum and difference products of the LO and RF frequencies, as described mathematically below.

Two laser lines produce LO signal at $2\sqrt{I_{01}I_{02}}\cos[(\omega_{01}\pm\omega_{02})t+\phi]$ $I_0 = I_{01}+I_{02}$

Photocurrent: $i_D = \frac{\alpha I_0}{2L_{MOD}} \left\{ 1 \pm \frac{1}{2} m M \sin[(\omega_{LO} \pm \omega_{RF})t + \phi] + M \cos(\omega_{LO}t + \phi) + m \sin(\omega_{RF}t) \right\}$ (Eq. 3)

In this case, the frequency conversion efficiency depends on the modulation efficiency m of the optical modulator and on an optical-heterodyning efficiency parameter, M , that can be made approximately equal to unity by setting the intensities and polarizations of the two phase-correlated lasers. Note that if the net gain of the RF-photonic link involving these components is unity, the frequency conversion efficiency of that same link can be -6 dB, which compares well with the conversion efficiency of electronic mixers. [6]

3.3.3 RF-Photonic Transversal Filters: We discussed above how RF-photonic links can be used for RF delay lines and also discussed implementations of optical combiners and splitters. A RF-modulated photonic link can be cascaded with a set of delay lines to implement a filter for the RF waveform. Figure 10 provides a generic illustration of the transversal filter that is implemented. [7] This filter is known as a finite-impulse-response (FIR) filter and comprises a number of delay paths, of differing delays and gains (amplitude weights) whose outputs are combined together. The RF-modulated optical signal is distributed to the set of optical delay paths, which could consist simply of optical fibers trimmed to different lengths. The RF outputs of the photodetectors located at the ends of the delay paths are then combined together. Bandpass filtering is realized at those frequencies for which the RF signals combine constructively.

There are many alternative approaches for constructing RF-photonic FIR filters besides the one illustrated in Figure 10. These alternatives have characteristics such as permitting tuning of the bandwidth and/or center frequency of the filter (by adjusting the lengths of the delays), adjustment of the window function of the FIR relationship, and realization of various bandpass responses. [8,9] Non-photonic implementations of FIR filters, such as those involving tapped RF delay lines, have been used in previous RF systems. The advantage offered by the RF-photonic approaches is that the filtering function can be added as an enhanced feature of the RF-photonic link that is also used for its other benefits, such as in antenna remoting or signal distribution.

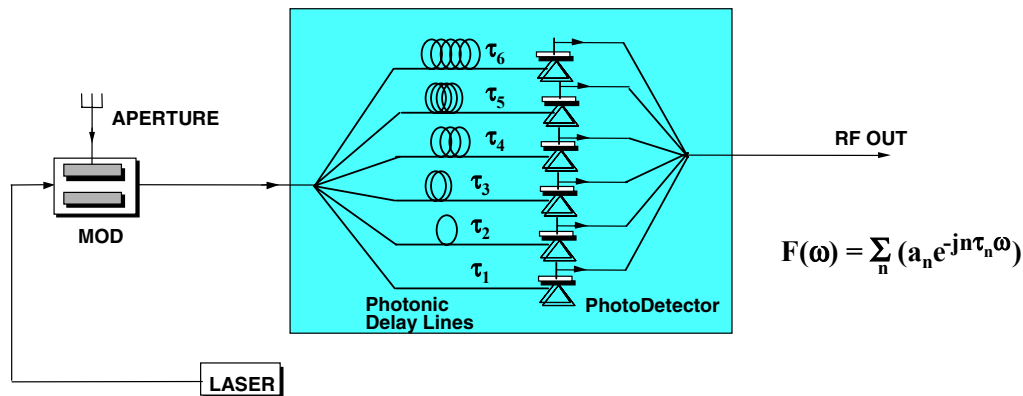


FIGURE 10 - Illustration of a Generic RF-photonic Filter

3.3.3 (Continued):

The transversal filter combines different samples of its input waveform that are taken at different times. Since multiple samples of the waveform are taken, the frequency response of the filter is periodic. The time interval between those samples, i.e., the difference between the delays of successive delay lines, determines the frequency spacing between successive occurrences of the passband. An advantage of the optical delay lines is that their delays can be quite long. For example, if the delay lines have lengths that differ by increments of 400 meters, the frequency spacing between passbands would be 1 MHz. Filters that have narrow passbands or whose passbands have abrupt edges are obtained by using a large number of the parallel delay lines (many terms in the FIR relationship). Filters that have low sidelobes (high out-of-band rejection) can be obtained by proper adjustment of the gains of the various delay paths. Out-of-band rejection better than 35 dB has been demonstrated in the RF-photonics filters. [10] Note that the broad bandwidth of optical delay lines permits filters that operate at very high frequencies as well as at low frequencies.

- 3.3.4 RF-Photonic Sampling of Analog Waveforms: An analog-to-digital converter performs the basic functions of sampling a continuous-time analog waveform and then digitizing the analog-valued samples. The RF-photonics link can be used to perform that sampling by replacing the laser of the link with a source of optical pulses. An actively mode-locked laser generates a train of optical pulses that have a width of several picoseconds, which is essentially an impulse compared to the RF waveform. The pulse rate is set by the frequency of an electronic oscillator reference to which the laser is locked, with typical pulse rates being 0.1 to 10 GHz. The phase noise of the mode-locked lasers has generally been limited by the noise of the electronic oscillator to which they are locked. [11] The optical modulator of the link is the sampler and the sampled electrical output is produced by the photodetector of the link. Thus, an analog-to-digital converter can be achieved by combining the optical-pulse-fed RF-photonics link with an electronic digitizer (or quantizer). [12] Like the simple RF-photonics links described above, this RF-photonics sampling link can be also used to remote the antenna from a digital receiver, to apply selected delays, to distribute the optical sampling waveform to various antenna inputs and to switch the sampled signals among various receivers.

3.3.5 Use of RF Photonics in Digital Systems: The advances in both the resolution and conversion rates of analog-to-digital converters (ADCs) have led to the incorporation of such ADCs closer and closer to the antennas. Some RF-receiver architectures that involve lower frequencies (e.g., UHF/VHF) envision placing the ADC directly at the antenna aperture. Other receiver architectures place the ADC further down the frequency down-conversion chain of a receiver to digitize the signal at a first-, second-, or third-level intermediate frequency (IF). Besides considerations of the signal frequency and the resolution required for the analog-to-digital conversion, the decision of where to place the ADC also depends on factors such as the environmental and size-weight-power (SWP) constraints at the antenna site. RF-photonics offers a useful enhancement to digital receiver systems whenever there is a need to locate any of the components associated with the digital receiver process remotely from the antenna site. These components may include the ADC circuit itself, the clock source (which may be an ultra-stable oscillator), frequency converters, local-oscillator (LO) sources, filters and amplifiers. Likewise, RF-Photonics also can be useful in antenna transmit systems that involve digitally synthesized waveforms.

Perhaps one of the greatest benefits of RF-photonics is obtained when certain sensitive or expensive hardware such as an ultra-stable oscillator needs to be shared among a large number of antennas or antenna elements. As an example, sensors such as radar systems that can detect slowly moving objects require LO and clock signals that have very low phase noise. The oscillators that produce such ultra-stable signals are expensive and are sensitive to harsh environments. Even when all of the mixers and ADCs for a receiver can be located directly at the antenna site, RF photonic links can be used to distribute the ultra-stable LO and clock signals to those mixers and ADC circuits. [3,13] The application of RF photonic links for distributing and switching such LO and clock signals was discussed earlier in this section.

In many combinations of platforms and RF systems, the SWP and cost of the ADC or the digital waveform generator preclude their placement directly at the antenna sites. If the frequency converters can be located at the antenna sites, the RF-photonics links would carry the IF analog signals. Alternatively, if the frequency converters were co-located with the digital receivers and generators, the RF-photonics links would carry and distribute the analog signals at their higher, free-space transmitted, frequencies. In these cases, the main components that would need to be located at the antenna site are the optical modulators and photodetectors and any electronic low-noise driver amplifiers and transmit power amplifiers that are coupled between the antenna elements and the modulators and photodetectors, respectively.

3.3.5 (Continued):

The RF-photonic LO generation, frequency conversion and waveform filtering methods discussed previously can enhance the capabilities of digital receiver and digital synthesizer based systems. One benefit is that with RF-photonic frequency conversion, the analog signal can be converted directly between the frequency handled by the ADC or digital synthesizer and the frequency received/transmitted at the antenna, without having to go through multiple stages of electronic frequency conversion. The large bandwidth and low dispersion of the photonic components permit large frequency differences between the LO, RF and IF signals. Note that a photonic transversal filter of the type discussed previously can filter the signal while it is in the optical domain. Thus, a second benefit is that the dynamic range requirement for the ADC and the sample rate and resolution required of the digital synthesizer can be relaxed.

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3.4 Summary:

Optical fiber is a medium ideally suited for digital communication. Optical communication over fiber has limited dynamic range. This is a key challenge for application of RF analog communications. Detectors tend to be noisy limiting receiver sensitivity, transmitter maximum power is limited by the physics and reliability of the current technology, and the medium becomes nonlinear when power levels are raised over a few tens of mille watts. Additionally, modulators tend to have limited dynamic range and the currently available amplifier technologies do not have the same low level of noise figures as their electronic counterparts. Digital communications, on the other hand, does not have the same level of dynamic range requirements as RF analog communications. In fact, with the application of error correction, the signal to noise ratio of a link can become incredibly poor without impacting the bit error ratio.

Although there are a number of challenges to the application of optical fiber as a new medium for RF analog communication, a number of the technical hurdles have already been overcome for commercial applications such as television distribution. New technologies continually show promising results and the payoff for their development are big. This guide describes the benefits that optical fiber provides, it covers some of the tradeoffs required in the design of RF communication links, and it describes some of the components and technologies available today from which to build a link.

4. RF PHOTONICS SYSTEMS CONSIDERATIONS:

As wideband device technologies advance, multifunction RF system approaches become more attractive for advanced platforms: manned and unmanned vehicles. An integrated-aperture RF system using multi-element arrays requires relatively complex RF distribution systems (coax cables, waveguide, power dividers/switches, filters, etc.). This fact raises issues related to the complexity of RF distribution and routing configurations, system performance, and platform installation impacts. RF photonics technology has progressed to the point where it provides a viable alternative for various aerospace platforms to the complex RF distribution systems that traditionally favor bulky coax cables and complex switch matrices.

This section includes discussions of traditional frequency bands of RF systems, overall RF systems architecture with RF photonics technologies, modulation techniques, and other integrated system considerations for both analog and digital signals.

4.1 Frequency Bands of RF Systems:

Depending on the functions of RF systems, they operate at different RF frequency bands. Since the radar frequency bands were coded with letters for security reasons during WWII, letter designations for RF frequency bands have been widely used. Examples of letter designations for radar and other RF systems are listed in Table 1.

TABLE 1 - RF Frequency Band Designations

Radar Bands		Other General Usage Frequency Designation	
Band Designation	Frequency Range (MHz)	Band Designation	Frequency Range (MHz)
HF	3 - 30	A	0 - 250
VHF	30 - 300	B	250 - 500
UHF	300 - 1,000	C	500 - 1,000
L	1,000 - 2,000	D	1,000 - 2,000
S	2,000 - 4,000	E	2,000 - 3,000
C	4,000 - 8,000	F	3,000 - 4,000
X	8,000 - 12,000	G	4,000 - 6,000
K _u	12,000 - 18,000	H	6,000 - 8,000
K	18,000 - 27,000	I	8,000 - 10,000
K _a	27,000 - 40,000	J	10,000 - 20,000
mm	40,000 - 300,000	K	20,000 - 40,000
		L	40,000 - 60,000
		M	60,000 - 100,000

4.2 RF Systems Architecture with Insertion of Photonics Technologies:

4.2.1 Suitability of Multi-Mode Optical Fiber for RF-Photonic Systems:

4.2.1.1 Characteristics of Multi-Mode Optical Fibers: A key consideration for the RF photonic system is whether it is based on multi-mode optical fibers (MMF), single-mode optical fibers (SMF) or a combination of them. Single-mode fiber systems have the attractive characteristics of extremely low optical loss, extremely wide signal bandwidth, and low dispersion, as discussed previously in 3.1. Other advantages support the use of large core (>50 micron diameter core), multi-mode fiber (MMF) systems over single-mode fiber (SMF ~9 micron core) systems in militarized, system-critical fiber optic links. Multi-mode optical fiber links for digital signals have been used successfully in dynamic environment, military platforms for many years including fly-by-wire and other control systems. Some of the key advantages of MMF links include: the presently lower cost of the MMF and their fiber optic connectors as well as the reduced sensitivity of the MMF cable connections to dust, vibration, and misalignment. These factors result in reduced material, installation, and maintenance cost as well as increased reliability of the link. As shown in Figure 11, the propagation loss of MMF is only slightly higher (by 0.1 to 0.2 dB/km at 1300 nm and 1550 nm wavelengths) than the loss of SMF. [1] This difference is almost negligible for the short links typically envisioned in aerospace platforms. However, there are limitations to using multi-mode fiber in RF systems that must be taken into account in their design. As discussed below, MMF provides a suitable alternative to SMF for simple remoting and delay-line functions when the lengths of the MMF links are short and the signal frequencies are low. However, some of the other potential applications for RF-photonics necessitate the use of single-mode fibers. These include applications that involve optical wavelength-division multiplexing, very short RF pulses, and optical heterodyning.

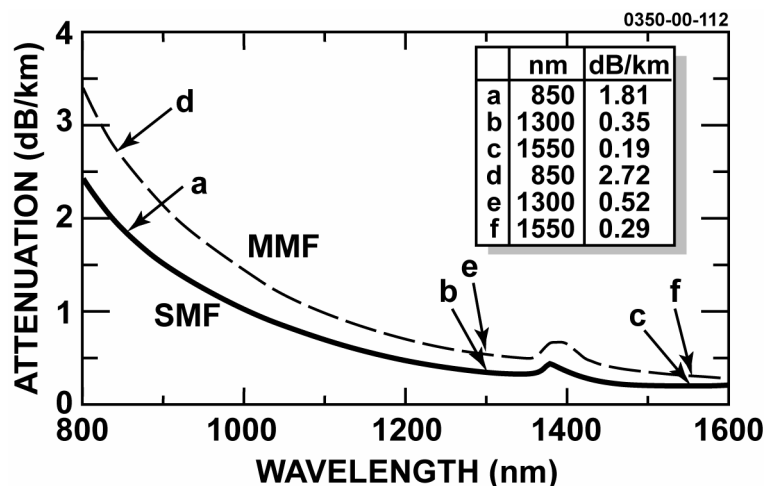


FIGURE 11 - Transmission Loss in Single-Mode and Graded-Index 62.5/125-Micrometer Optical Fibers [1]

4.2.1.1 (Continued):

Multi-mode optical fiber is physically different from single-mode optical fiber due to the larger core diameter (62.5 μ m is typical). This difference results in the presence of multiple “modes” of light traveling down the fiber as opposed to the single “mode” of light in a single-mode fiber. These modes represent different paths the light can take in traversing the optical fiber whereas a single-mode fiber, by definition, only supports one path for the light to follow (at a given wavelength). Each of these light paths, or modes, travels with a different velocity, or propagation constant, resulting in modal dispersion. Modal dispersion results in spreading of the optical signal as it is transmitted down the fiber optic cable and can be detrimental to link performance (similar to dispersive effects in RF cable).

4.2.1.2 Performance Limitations of RF-Photonic Links with Multi-Mode Optical Fibers:

RF Link Bandwidth

MMF has an inherent bandwidth limitation as a result of modal dispersion. This limitation is usually given as a bandwidth*length product that determines the maximum bandwidth for a given length of multi-mode fiber. This limitation is approximately 500 MHz*km for typical MMF when the input light to the MMF overfills the core of the fiber. [2] Some multi-mode fibers have a bandwidth-length product as high as 2000 MHz-km. Additional complexity is added by the fact that the maximum bandwidth can vary by 3 to 4 times even for a fixed length of fiber by simply varying the modes which the fiber is carrying [3,4]. This is done, either accidentally or intentionally, by (1) varying the launch condition into the MMF [3,4], or by (2) varying the position of bends in the fiber itself. These changes have the ability to determine which modes carry the most optical power and the distribution of the light intensity at the output face of the fiber. Given these considerations, sufficient care must be taken to account for these bandwidth and output intensity variations when a MMF link is used for high dynamic range, high-frequency analog link applications.

As an example, Figure 12 shows the results of one comparison of a SMF link and several MMF links. The RF S_{21} response curves are shown in the figure. The frequency response shown for the SMF link is limited by the characteristics of the optical modulator and the photodetector used in this measurement. These device limitations are evident in the observed drop-off in gain at frequencies below 4 GHz and above 14 GHz. This result is NOT a bandwidth limitation of the single-mode fiber. The response of the 25 m MMF link has the same general shape as the response of the SMF link. Although both the 25 m-MMF and SMF link response curves still have features, these are typically due to factors such as cable losses, optical and electrical reflections, and impedance matching between the photodiode chip and housing, and not to the fiber itself. The similarity is clear when comparing the curve shape of the SMF and 25 m MMF links. The response for the 25 m MMF link is stable under variations in fiber position and launch condition, signifying that the link is within the bandwidth length product limitation of the 62.5 μ m core-diameter multi-mode fiber used for the measurement.

4.2.1.2 (Continued):

The RF S_{21} response for a 50 m MMF link also is shown in Figure 12. It is clear from this trace that there is a slight gain slope reducing the gain by about 4 to 5 dB over the 6 to 15 GHz range. This gain reduction is not present in the SMF link. This suggests that for 50 m lengths, one is probably operating near the bandwidth limit of the multi-mode fiber. Thus, for such large RF signal bandwidths and link lengths, the performance of a MMF link is not optimal (reducing the link's frequency response) and RF link performance would be improved by the use of single-mode fiber. Note, however, that it may still be possible to use MMF links to carry high-frequency RF signals without degradation if those signals have a limited bandwidth. [5]

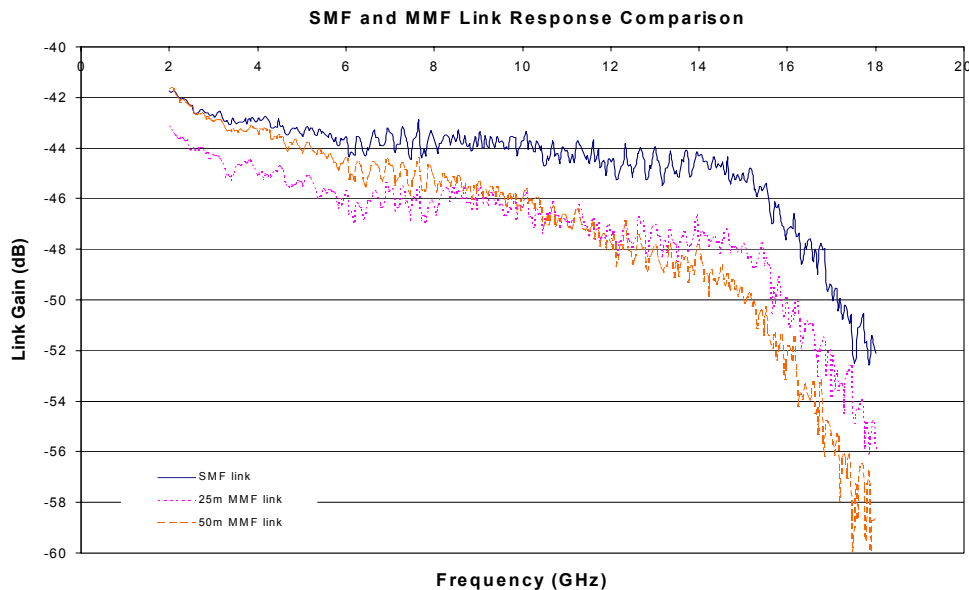
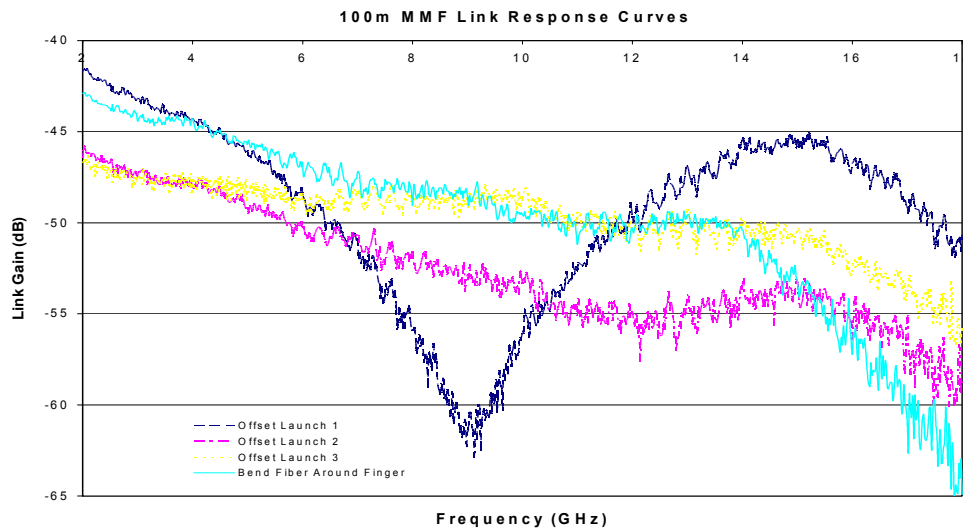


FIGURE 12 - Fiber Link Response Comparison [6]

4.2.1.2 (Continued):

Gain Flatness and Stability

The modal dispersion in multi-mode fiber also affects the RF gain (spectral) flatness and stability. As mentioned above, the distribution and relative phases of the energy in the various optical modes in a MMF can vary greatly as launch conditions and fiber position are varied. Therefore, depending on the length of the fiber, the gain flatness and shape may vary as the launch condition and fiber bends are varied. The goal, of course, is to achieve the gain flatness and stability of a single-mode link using multi-mode fiber while being immune to changes in launch and fiber conditions. Figure 13 shows sample S_{21} response curves of a 100 m long MMF link measured for various launch and fiber-bend conditions. From these three curves it is clear that the 100 m link performance is highly dependent upon the launch condition and the fiber environment. These tests were performed using commercially available single-mode lasers, modulators and photodetectors. [6]

FIGURE 13 - 100 m Multi-Mode Link S_{21} for Various Fiber/Launch Configurations [6]

4.2.1.2 (Continued):

It is interesting to note several performance features of a 100 m MMF link from the curves in Figure 13. First, the shape of the response varies greatly from condition to condition as is seen by inspecting the shape of each of the curves. Second, the flatter response curves have less optical power hitting the photodiode as seen by observing the gain levels at 2 GHz for all three curves. Finally, a change as subtle as bending part of the fiber towards the front or back end of the link (i.e., "Bend Fiber Around Finger" trace) can result in improved flatness and increased gain at 2 GHz whereas a bend in a SMF link would simply increase the loss over the entire spectrum. This improved gain flatness is the result of redistributing the modes in the fiber to be similar to that of a center-launched, maximum bandwidth configuration. Similarly, these response curves depend upon the coupling of the MMF to the photodiode. These widely varying response results signify that the link is operating near its bandwidth*length product limit and the performance is highly sensitive to fiber position and launch condition. This link could be operated in this regime, but performance would not be reliable over a dynamic environment unless only a limited bandwidth (e.g., 2 to 4 GHz) was required.

Signal Pulse Delay and Shape

Pulse delay and shape tests were done with signals having pulse width of 89 psec full-width half-maximum (FWHM) and 10/90 rise time of 57 psec. [6] The test signals have a 90/10 fall time of 139 psec. Comparisons were made of a 1 m long SMF link, a 300 m long SMF link and a 100 m long MMF link. Propagation delay times varied, as expected, with fiber length (~5 ps/m). Observations of the output pulses show an increase in pulse width and rise time for a 100 m MMF link over the 300 m SMF link. Fall times did not vary significantly for the various links tested and no change in pulse shape or number is usually observable. The 10 to 15 psec increase in the pulse FWHM for the MMF link versus the 300 m SMF link is accounted for by the observed change in rise time. This behavior can be explained in terms of modal dispersion. The fact that modes propagate at different speeds unless properly tuned causes the arrival time to "smear out" the energy in a fast rising edge broadening out the rising edge of the pulse. In even longer lengths of fiber, the energy in the delays of the degenerate mode groups can be time resolved, thereby producing separate pulses in time [3,4]. This in fact is already evident in Figure 13 for the zero offset case where a discreet delay difference is inferred from the dip in the transform at approximately 9 GHz.

RF Signal Spectrum

Given the multi-mode nature of a 62.5 μm diameter fiber, one can expect that the presence of various modes with different velocities would result in phase noise at the photodiode. [6] These effects show up as a broadening of the RF spectrum after passing through the multi-mode fiber.

- 4.2.1.3 Use of Multi-mode Fiber with Multi-Mode Photonic Devices: The test data discussed above indicate that for link lengths less than 50 m (and RF signal frequencies below 10 GHz), similar performance can be achieved when a 62.5/125 μm multi-mode fiber is used in place of a single-mode fiber. At lengths of 50 to 100 m the MMF performance is on the lower edge of the bandwidth*length product for the MMF and suffers from an increase in high frequency loss (-3.3 dB at 15 GHz). MMF lengths of 100 m+ are extremely sensitive to both fiber launch conditions and fiber position reflecting the dependence of the multi-mode fiber bandwidth on the modal distribution. These tests were performed with single-mode lasers, modulators and photodetectors, operating at 1550 nm wavelength, and indicate that the minimum bandwidth*length product of the 62.5 μm fiber used in the tests is about 500 MHz*km (i.e., 20 GHz*25 m). This is a reasonable value since most multi-mode fiber specifications give bandwidth*length products ranging from 200 MHz*km to 2000 MHz*km.

Mixing multimode and single-mode devices in general is not recommended and requires special engineering consideration to design for proper operation. The performance of short MMF links coupled to single-mode photonic devices can be close to that of SMF links, especially when going from smaller to larger diameter cores (e.g., SMF to MMF). This performance is enhanced when that coupling is adjusted to overfill the MMF by defocusing the light from the single-mode photonic devices. Thus, the optimal optical-fiber pigtail for a device is different if that device is to be used in a SMF link or in a MMF link. Nevertheless, the desire to overfill the MMF makes the pigtail task for a MMF no easier than the pigtail task for a SMF. An interesting consideration is whether multi-mode photonic devices such as typical vertical-cavity surface-emitting lasers (VCSELs) and large-area photodetectors could be used in a MMF optical link. Optical coupling between a photonic device and the MMF would be simplified, in the same way as coupling between a pair of multi-mode fibers, if the diameter of the photonic device is as large as the diameter of the core of the MMF. The modulation bandwidth of these large-area VCSELs and photodetectors is limited primarily by their capacitance. For example a photodetector having a diameter of 50 microns has a 1-dB modulation bandwidth greater than 7 GHz. When all of the light from a MMF can be captured by the large-area photodetector, the link response will be less sensitive to variations in the launch conditions and the mode-energy distribution in the fiber.

Vertical-cavity surface-emitting lasers have been used in combination with multi-mode optical fibers for digital optical data links. These lasers are available primarily at an emission wavelength of 850 nm, although VCSELs emitting at 670 and 1300 nm also have been made. The large diameter (typically 8 microns or larger) of the VCSEL makes alignment to optical fiber easier. However, those multi-mode devices typically have higher relative intensity noise (generally above -140 dBc/Hz) than single-mode, single-frequency lasers (below -155 dBc/Hz). [8] This can degrade the SFDR of analog links. The performance of RF links containing multi-mode VCSELs and multi-mode fibers has been evaluated. SFDR greater than 95 dB-Hz^{2/3} has been observed for signal frequencies between 1 and 10 GHz. [8,9] Thus, multi-mode fiber links having multi-mode photonic devices can be suitable for some analog RF applications.

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4.2.2 Selection of Optical Wavelength for RF-Photonic System: Selecting the wavelength for an RF photonic link requires a balance between system performance and component availability. Specifications such as RF frequency band, bandwidth, and link length are as critical to wavelength selection as are the performance requirements. Performance requirements may be linear dynamic range, intermodulation-free dynamic range, phase noise, pulse dispersion, etc. System architecture may also influence wavelength selection. Each of these contributors to optimization of system wavelength is discussed in more detail below.

4.2.2 (Continued):

Three wavelength bands are available to the designer of RF photonic links. They are loosely defined as the first, second and third telecommunications windows and centered at 850 nm, 1310 nm and 1550 nm, respectively. The first window, at 850 nm, is traditionally used for multimode applications. Rarely is this wavelength band used for single-mode applications for two reasons:

- single-mode waveguides at 850 nm are very small, roughly 3 microns in diameter, that presents problems for coupling and reliable connectorization, and
- higher frequency applications usually require external modulation, often achieved with lithium niobate MZMs, that are susceptible to optical damage at shorter wavelengths when high optical power is used.

That does not mean that there are no advantages to designing systems in the 850 nm band. Direct modulation at 850 nm is possible up to frequencies of around 3 GHz. A 3 GHz RF photonic signal can span 50 meters or so of 50-micron core multimode fiber without significant signal degradation from modal noise and dispersion. Because 850 nm optical components are relatively inexpensive, this may be an attractive solution for some applications. The majority of installed digital fiber links in aerospace applications are directly modulated 850 nm links connected via multimode fiber, albeit with larger, 100-micron, cores.

The second telecommunications wavelength window centered at 1310 nm is significant for 2 reasons: (1) this wavelength experiences negligible dispersion in single-mode fiber and (2) semiconductor optoelectronic devices are more efficient around 1310 nm. Semiconductor lasers are often more efficient when designed and operated at 1310 nm. Hence, lasers designed and implemented using similar technologies will produce greater optical powers at 1310 nm than if they are designed for 1550 nm operation. Similarly, photodetectors generally have higher responsivity at 1310 nm than they do at 1550 nm. Both multimode and single-mode links are common at 1310 nm.

Systems that require optical amplification or that benefit from wavelength division multiplexing (WDM) generally are designed to operate in the third telecom window at 1550 nm. This selection is due to the wide availability of erbium-doped fiber amplifiers that operate in this wavelength band. No similar device is available at 850 or 1310 nm. Semiconductor optical amplifiers can be made at 850, 1310 or 1550 nm, but they pale in comparison to EDFA performance (see 6.1.5.2). Availability of EDFAs for the 1550 nm band has resulted in preference for this band in telecommunications applications and driven the design of most WDM components within this wavelength.

4.2.2 (Continued):

The 1550 nm band also coincides with the absolute minima of optical absorption in most silica optical fibers. Most RF photonic applications require a relatively short length of fiber, so there is little motivation for selecting 1550 nm operation based solely on fiber losses. The dominant losses in an RF photonic link are outlined in Section 5 where the contribution to link loss due to optical

The 1550 nm band also coincides with the absolute minima of optical absorption in most silica optical fibers. Most RF photonic applications require a relatively short length of fiber, so there is little motivation for selecting 1550 nm operation based solely on fiber losses. The dominant losses in an RF photonic link are outlined in Section 5 where the contribution to link loss due to optical absorption is dismissed as negligible.

There are other wavelengths available. For example, one major aircraft program is using 980 nm for data. 1060 nm is also an option. Any wavelength with a source and receiver is an option if the fiber will support it. However, the industry has centered its attention on the three basic windows.

In summary, three wavelength bands are available to the RF photonic systems designer. The first band at 850 nm is generally reserved for relatively low frequency (<3 GHz) point-to-point RF links over multimode fiber. The use of multimode fiber will limit the fiber link length to less than 50 meters at 3 GHz. Typically, the 850 nm band is used only for digital point-to-point applications over multimode fiber. The second band at 1310 nm is generally used for point-to-point RF photonics links over either single-mode or multimode fiber. A combination of high laser power, high photodetector responsivity, and availability of efficient modulators make this an excellent band for RF photonic applications assuming neither optical amplification nor WDM are required. Finally, the 1550 nm band is often the most commonly used wavelength due to the amount of flexibility (and wealth of components) available in design. Single-mode RF photonics links have been demonstrated above 40 GHz using both 1310 nm and 1550 nm systems. Final selection of the wavelength band for a given system will come down to a trade-off of the considerations listed above.

- 4.2.3 RF-Photonic Signal Distribution and Switching Architectures: RF signal-distribution architectures generally involve point-to-point links between modules, for example between a sensor aperture and an exciter or receiver. Switching of signals, for example to/from different portions of a filter bank, involves changing the path for a point-to-point connection. Only specific system functions involve splitting or combining of signals, for example to/from the various radiating elements of phased array antennas or to a combination of a channelized receiver and a cued receiver. This type of signal-distribution architecture is motivated in part by the need to maintain isolation between the separate links.

4.2.3 (Continued):

RF-photonic links are useful for such point-to-point architectures. Examples of applications for RF-photonic links are described in 3.2 of this document and include antenna remoting and delay lines for various functions (including antenna beamforming and radar false-target generation). Other RF-photonic links also can be made to perform additional functions such as LO generation, frequency conversion, sampling and transversal filtering, as described in 3.3. The RF-photonic point-to-point architectures resemble their RF-cabled counterparts. Optical switches could be used to change the path of the RF-modulated optical signals in much the same way electronic switches are used for RF signals, as illustrated in Figure 14a. Various types of optical switches are described in 6.2.5.

It is possible to multiplex a number of RF/analog signals onto the same optical fiber. This capability is enabled by the large bandwidth of optical fiber and the availability of optical wavelength division multiplexing (WDM) components. The optical-fiber transmission medium is subdivided into a number of optical-wavelength channels, in much the same way as the frequency channels in radio communications. In a WDM link, as illustrated in Figure 14b, each signal is modulated onto an optical carrier having a different wavelength. Signals can even be routed through a WDM network according to their wavelength. WDM networks are being developed by the telecommunications industry for optical distribution of digital signals. Use of WDM networks to optically distribute a combination of digital and analog signals is being investigated by some research groups. [1] One possibility under consideration is to separate analog and digital channels between 1310 nm and 1550 nm, respectively.

One example of an optical WDM-based point to multi-point architecture for signal distribution and switching is described in 3.2.4. This “broadcast star” architecture is illustrated in Figure 14c. [2] In one example, the wavelength of the optical carrier is used to designate the source of the RF signal, which is carried on a particular WDM channel. Each receiver contains a tunable optical filter to enable that receiver to select its desired WDM channel. Presently available tunable filters have a RF-signal selectivity of 50 to 60 dB or better.

Many digital-signal distribution architectures are based on data-bus configurations that make each signal potentially available to all nodes of the network, in contrast to the prior point-to-point architectures. At each node, a signal could be added to the data bus or dropped from the data bus. Each signal is assigned a descriptor or address that is used by a node to determine whether that signal is accessed by that node or is passed on to the other nodes of the network. Multiple digital signals that are of finite duration or that have a smaller bandwidth than the bus bandwidth can be multiplexed together onto the same set of cables that interconnect the various nodes of the network. The interconnection architecture of these data-bus networks could have the nodes located in a ring or star configuration. Various formats such as Ethernet or Fiber Channel have been used for these optical data-bus networks.

4.2.3 (Continued):

An optical WDM data bus architecture is illustrated in Figure 14d. This network contains a number of wavelength-selective nodes that are interconnected in a ring configuration.[3] Each node can be connected to a generator and/or receiver of RF signals. For example, the RF signal generators might be various communications antennas that are distributed throughout a platform and the signal receivers could be a set of communications receivers that operate at a common IF. Although those antennas might provide to the data bus RF signals that are at a variety of RF-carrier frequencies, the RF-photonic LO generation and frequency conversion methods described in 3.3 could be used to translate from those various RF-carrier frequencies to the common IF. In one example, the various nodes connected to the antennas might be assigned specific wavelengths and the signal-receiver nodes could then be tuned to select a particular antenna signal. Presumably, the network would have more antenna-signal generators than receivers but those signal generators would not always be actively supplying signals to the network. Note that the same optical network also could be used to carry signals from a number of RF-signal sources or exciters to the same group of antennas. The wavelength of the optical carrier for the exciter signal would then be tuned to match the wavelength associated with the desired antenna. With such ring configurations it is important to establish some protocols to ensure that only one node is injecting a given optical wavelength into the network at a given time, thereby avoiding collisions. In this way, one avoids the situation in which two different exciters are trying to send signals to the same antenna.

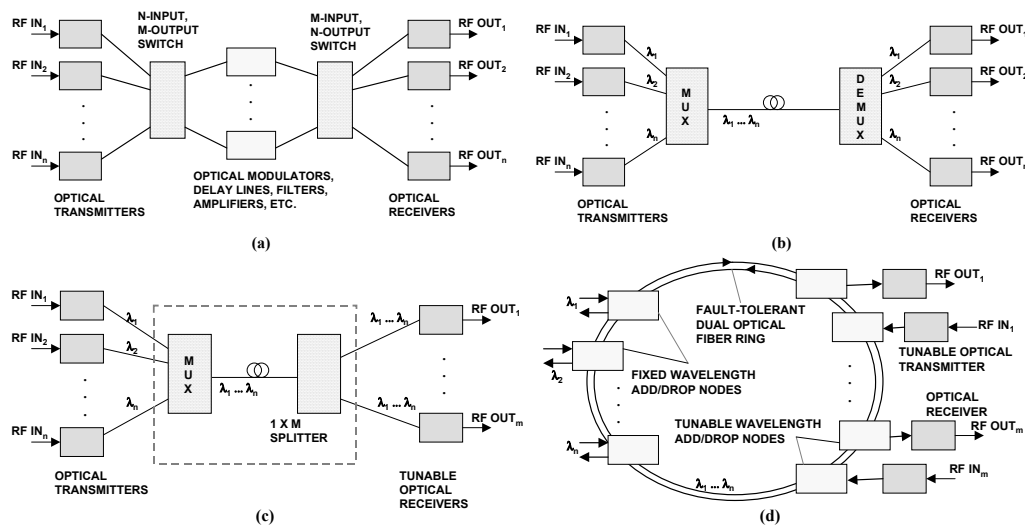


FIGURE 14 - Various RF-photonic signal distribution architectures involving (a) switched point-to-point links, (b) optical wavelength division multiplexing of signals, (c) point-to-multipoint links with wavelength selection, and (d) data bus ring configuration with wavelength selection.

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- 4.2.4 Considerations for Multiplexing of Analog and Digital Signals: Optical fiber has an advantage compared to electrical wires in that multiple fibers can be bundled together into a single cable with negligible crosstalk incurred between the optical signals carried by the different fibers. In contrast, each electrical signal carried by wire has to be contained in a separate shielded cable to ensure sufficient isolation. A further advantage is that multiple optical signals can in fact be carried by the same optical fiber using the technique of optical-wavelength multiplexing (or wavelength division multiplexing, as the technique is called in the telecommunications industry). Wavelength division multiplexing (WDM) is becoming a common approach for fiber-optic communications networks, which carry digitally modulated optical signals. One also could use WDM to multiplex a number of analog as well as digital signals onto the same fiber for aerospace applications.

In WDM, each signal is typically modulated onto an optical carrier of a different and specific optical frequency. The International Telecommunications Union has specified a set of frequencies, or channels, for WDM and most commercial photonic WDM components are matched to this standard. The frequency spacing between adjacent channels is typically a fixed value of 50 or 100 GHz. Commercially available optical multiplexer components combine the signals from many optical frequencies onto a common output fiber and other commercially available optical demultiplexers separate and disperse the multiplexed frequencies supplied to them into a number of output fibers. The adjacent channel isolation of these demultiplexers is sufficiently low (typically 25 to 30 dB in the optical domain) that RF crosstalk from the multiplexing is below 50 to 60 dB. Additional stages of optical filters could be added to further reduce the crosstalk to below 100 dB.

- 4.2.4.1 Optical Non-Linearities in Fiber: Some care should be taken when more than one analog signal is carried on the same optical fiber, because of non-linearities in the optical fiber material. These non-linearities, which arise from phenomena such as four-wave mixing and cross phase modulation, can produce noise and spurious signals in other channels. Although these non-linear characteristics are weak, they could become significant when the optical power in a signal is very high and/or when the length of the optical fiber link is very long. Digital signals typically involve very strong modulation of the optical carrier (i.e., large depth of modulation). The average optical power level is moderate, typically below 1 mW per channel. Thus, the effects of optical-fiber non-linearities are negligible given the lengths (<1 km) of typical links in aerospace platforms. In contrast, analog signals typically involve small modulation depths with much energy in the optical carrier to achieve large dynamic range. The power in the optical carrier could be greater than 10 mW, and even greater than 100 mW in some extreme cases. Thus, the presence of a strong analog signal in one WDM channel could affect the quality of a second analog signal that is multiplexed in a nearby WDM channel on the same fiber.

Cross phase modulation arises from the weak dependence of the optical refractive index of the fiber on the average intensity of the light in all of the multiplexed channels. For a 1-km length of fiber, that average intensity would generally have to be greater 1 watt for cross phase modulation to be significant. Temporal or data dependent fluctuations in the average intensity produce temporal or data dependent fluctuations in the delay that the analog signal experiences in traversing the optical fiber link. Two application areas in which this fluctuation in delay could be important are those of antenna beamforming and of photonic generation of RF signals by optical heterodyning.

A second non-linear phenomenon is four-wave mixing. Four-wave mixing arises from an optical-fiber-material assisted interaction between signal or carrier components (optical waves) at three or four different optical frequencies. In order for that interaction to occur, a phase-matched, or phase-balanced condition must exist for the collection of three or four optical waves. This phase-matched condition is fairly easy to achieve for single-mode optical fiber when the frequencies of those optical waves are all within approximately 100 to 200 GHz of each other. The phase matching is poorer, and thus the four-wave mixing effect is weaker, when the frequencies of the waves are spaced more widely apart, or for light carried in multi-mode optical fiber.