Photonic Beamforming Technologies for Advanced Military and Commercial SATCOM Antennas

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Abstract—Photonically implemented beamforming requirements, architectures, and technologies are discussed for application to military and commercial SATCOM antenna systems. Several general performance requirements motivate the use of leverage from photonics beamforming to facilitate the effective implementation of future SATCOM antenna systems. A wide variety of beamforming architectures and techniques have been examined for applicability to these systems. The most attractive candidates are described as are the key photonic technologies that will enable the eventual implementation of these systems.

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1. INTRODUCTION

There is emerging in the telecommunications industry a significant demand for the broadband wireless transmission of voice, video, and data to highly mobile users. Several commercial ventures to provide these services are underway and several more are well in the planning stages. Commercial service providers must be able to establish capacity and coverage on demand and in as small and manageable increments as possible. These services must compete in terms of cost and quality of service with those originating from established and nearly ubiquitous land based wireless and fiber communication networks. Military and government users are similarly demanding the availability of high capacity, highly reconfigurable and highly robust wireless communications with levels of performance comparable to or exceeding those required for commercial systems. Shrinking budgetary resources for government applications are also a major consideration as there is an expectation for advanced systems to provide enhanced performance, capability, and reliability but at a significantly reduced cost.

The use of photonics to enable the development of these next generation SATCOM systems is a subject of increasing interest. TRW has recently completed a technology trade and architecture development study to investigate the use of photonics technologies and techniques to facilitate beamforming in SATCOM antennas. This study was sponsored by the AFRL Rome Laboratory to support the evaluation and development of photonic beamforming for next generation MILSATCOM systems. Our conclusions are equally applicable to the establishment of photonically implemented antennas for both military and commercial systems. This paper describes i) the principal requirements of these systems, ii) the several important beamforming architectures that deliver the maximum leverage from photonics relative to conventional radio frequency (RF) electronic implementations, and iii) the critical photonic technologies that will enable the implementation of these antennas in spaceborne SATCOM systems.

2. GENERAL PERFORMANCE REQUIREMENTS

There are several key requirements for these antenna beamforming architectures that motivate our interest in the application of photonics technologies. They can be characterized as being principally concerned with the realization of improved performance or reduced cost. The first requirement is for a large number (from 10 to 50) of independent, electronically steerable beams. These individual beams must be steerable to any region (urban or rural) that would contain ground terminals within the full Earth coverage field-of-view. The individual beams may be required to support the simultaneous reception of a substantial number of frequency-division-multiple access channels covering aggregate bandwidths of up to several Gigahertz. The drivers for many beams supporting channels over many frequencies is the potential for increased total capacity and revenue. Increasing the number of simultaneous beams can drastically increase the complexity of the beamforming network structure and represents a significant challenge for antennas implemented entirely in electronics. True time-delay structures may also be required for wideband beamforming in either array feed structures or in direct radiating phased arrays. Electronically based true time-delay beamforming structures are difficult and generally regarded as costly to implement.

A second requirement is RF performance such as gain, noise figure, and dynamic range. Most high data rate personal...
communication systems will be implemented in Ka or Q band covering a range of frequencies from 20 to 45 Gigahertz. Adequate gain and sensitivity is required to enable the high capacity transmission of data with the lowest possible transmit powers from the mobile units. Military systems generally impose the most aggressive requirements for dynamic range, but large-scale, high-capacity commercial systems may require a high level of dynamic range performance. The beamforming network should therefore incorporate low loss structures that can operate over wide frequency bandwidths and provide adequate RF performance to meet the necessary system requirements. Communication antenna systems are generally specified for gain and sensitivity by a G/T requirement that incorporates both array gain and equivalent noise temperature. Consequently, both RF and photonic implementations can meet nearly every G/T requirement if enough elements or aperture area is employed. The real trade then becomes the cost associated with the architecture that meets the performance requirements. For high frequency antennas, the high packaging density in the feeds or among s as required to meet the performance specifications can represent a significant barrier to low-cost implementation.

A further requirement is reliability. Structural and architectural flexibility can lead to improved reliability through the possibility of remoting principal or secondary hardware from the antenna feed or array elements. Critical components can be protected from radiation, temperature variation, or shock and vibration. For those components that are environmentally robust, hardware remoting may equate to nothing more than providing some flexibility in the packaging of individual components or arrays of devices. Such considerations may be critical in providing durable and robust payloads to support space based, high capacity communication networks.

A final important and overriding requirement is for reduced size, weight, DC power, and cost. As mentioned previously, for nearly all implementations of antenna systems, the required levels of performance can be achieved with enough hardware and DC power. As such, all the requirements for a SATCOM system can be distilled to the principal measure of size, weight, DC power = COST. Cost then becomes the elucidative factor to the relative merit of one antenna implementation over another. Large numbers of beams must be consolidated in a single or few apertures. Reduced payload weight can lead to the use of a smaller launch vehicle or the incorporation of multiple spacecraft in a single launch vehicle. As a large portion of the satellite cost is associated with the launch vehicle, the successful incorporation of photonics must most drastically impact the cost of implementation.

3. BEAMFORMING/ARCHITECTURE TRADES

We have developed several beamforming architectures that leverage the use of photonics to address many of the critical implementation issues associated with achieving acceptable levels of capability, performance, and reliability at a reduced cost. We summarize here the conclusions of our efforts towards photonic implementations and illustrate some of the highest leverage insertions. There are two principal antenna structures that can enable simultaneous multiple beam operation. The first is a direct radiating phased array with element level phase and amplitude control. Active phase, and possibly time, and amplitude weighting is implemented at the element level to simultaneously steer many beams. For spaceborne transmit antennas, each beam must be individually formed and the signals to each radiating element multiplexed prior to radiation. Photonics can enable the phase weighting for beamforming and the signal combining necessary to transmit multiple simultaneous beams.
optical amplifiers, the amount of DC power required for an antenna incorporating the required number of elements for acceptable levels of performance can be as much as ten times that required for an equivalent electronically implemented array.

The second category of beamforming structures that more effectively enable the assembly of photonic beamforming receive antennas incorporates a circuit beamforming structure with a direct radiating array or an array feed. The beamforming geometry passively establishes the required phase, time, and amplitude weights to form many simultaneous beams. Examples of these types of beamformers are the Rotman Lens, Butler Matrix, or cluster combined Reflector Array Feed. Rotman lens antenna beamformers have been demonstrated in RF for two-dimensional arrays and in optics for linear arrays [1,2]. We have found that for the implementation of two-dimensional beamforming, RF printed circuit Rotman lens structures can be most effective in enabling multiple beam wideband operation. Rotman lens structures for two-dimensional arrays can be implemented entirely in photonics, but with a high level of complexity that is unattractive for almost all applications. Photonic beamformers are very attractive and can lead to significantly reduced size and weight. As illustrated in Figure 2 below, the beamformer for a linear array can be implemented with free space optics or with fiber or waveguide. The necessary signal combining can be realized through the use of optical wavelength multiplexers to reduce the impact of passive splitting loss. Although a useful application of photonic beamforming, the restriction to the use of linear arrays will severely limit the types of communication systems that can benefit from photonics insertion. Butler matrix beamformers can also be implemented for application to narrowband systems. For multi-access wide-frequency-coverage beamformers, the resulting beam squint can result in losses that negatively impact the antenna sensitivity and performance. Butler matrices can be implemented in optics, but requires optical coherence throughout the beamforming structure, which significantly increases the complexity associated with these types of beamformers.

Nevertheless, Rotman lens, or Butler matrix beamformers can be implemented in RF and photonics can be used for beam selection through the establishment of an N to M switching structure. Any type of circuit beamformer (Rotman lens, Butler matrix, or Array feed) requires the use of a switching structure that can select the necessary number of beams from the large number of beams that are available at the beamformer output. Most multiple beam circuit beamformers require the selection and routing of the weighted and combined signals to a smaller number of individual receiver processors. Photonics offers a great deal of promise for implementation of the switching structure that enables beam selection and routing. The problem of photonic switching is already being addressed for terrestrial based telecom networks. It is clear that these same technologies can find application to enabling beam selection in spaceborne communication antennas.

Reflector antennas with array feeds represent another type of circuit beamforming structure applicable to supporting moderate bandwidths and moderate scanning fields of view for receive antenna systems. Whereas with direct radiating arrays, the number of elements required is determined by the required level of sensitivity, reflector array feed antennas require only enough elements to form the necessary number of total beams. The reflector provides the gain required so to achieve the necessary G/T and individual beams can be formed through the combination of signals from a small cluster of feeds. Because of the use of the reflector and the additional gain it provides, fewer feed elements are required for adequate performance, which results in reduced cost and complexity. The key challenge is in collecting input signals only from those feeds necessary to form the required beams as illustrated in Figure 3 below.

The constrained feed Rotman Lens as illustrated in Figure 2(b) can be fabricated in low loss and highly compact
A straightforward photonically implemented beamforming structure for the spaceborne receive antenna is illustrated in Figure 4. Individual wavelengths are used and reused to enable RF signal combining. The optical power from a laser at a single wavelength is split and distributed to modulators at several antenna feeds. Other optical signals at different wavelengths are also split and distributed to the modulators associated with other feeds so that every cluster of seven feeds utilizes seven unique wavelengths in the formation of a single beam. Wavelength multiplexers are used to combine the optical signals while a switching structure enables the routing of the formed and selected beams to the required number of photonic receivers. In this manner, beams can be formed and selected in an efficient manner. For the formation of a large number of beams, this architecture can be very attractive because it enables the use of many beams with fewer elements than required for a phased array.

For the selection of a moderate number of beams, a switched routing structure is more appropriate for the conservation of laser power. This architecture incorporates photonic switching and routing for the formation and selection of individual beams and results in one half the size, comparable weight, and less than one half the required DC power relative to RF electronic implementations. Array-feed multiple-beam antennas do require some additional redundancy for reliability purposes as the advantage of graceful degradation with element module failures is lost with the array feed architecture. Additional switching can be incorporated at the feed elements or remotely. The hardware remoting that results from the use of photonics can work to facilitate improved reliability in these types of antenna beamforming structures.

4. CRITICAL PHOTONIC TECHNOLOGIES

For those transmit and receive antenna beamforming architectures described above, our investigation has identified several key photonic technologies that will enable the application of photonics to SATCOM antenna systems.

The first key set of technologies meet the need for distribution of optical power to moderate or a large number of antenna elements. High power, wavelength selectable semiconductor laser sources are necessary for the implementation of reflector and array feed antennas utilizing optically switched or routed beamforming structures. Semiconductor based DFB laser devices demonstrate much promise for providing high power, low noise optical carrier signals in a highly compact and robust package but currently do not meet the levels required to establish adequate system performance. With further development, these devices can facilitate high performance and robust antennas that meet the needs of next generation SATCOM systems.

For the distribution of optical energy to a large number of antenna elements, optical amplification is an absolute necessity. Low noise, high output power optical amplifiers

Figure 3 Reflector antenna with array feed.

Figure 4 Array feed beamforming architecture implemented with WDM combining.

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will enable the implementation of active phased array antennas to support high capacity systems. Semiconductors again represent a material that can enable highly compact and robust devices that enable low size and weight SATCOM payloads. Semiconductor materials also are likely to provide the radiation hardness demonstrated in semiconductor MMIC based RF devices and modules.

A second key set of technologies for enabling the implementation of direct radiation arrays and array feed antennas is photonic switching. Switching is most likely to represent a principal function in the implementation of both photonic and electronic antenna beamforming structures. There currently exists practically no RF and only a very few photonic switching technologies that can enable high performance operation. There are a few technologies are under development and described in the technical literature [3,4] that show promise for the application to SATCOM antenna systems. The demonstration and development of environmentally robust switching structures remains a topic of investigation, but preliminary reports indicate that the key materials can be expected to demonstrate hardness through typical levels of lifetime environmental (i.e. radiation, temperature, shock, and vibration) exposure.

A further set of key technologies relates to the electrical-to-optical or optical-to-electrical interface. The conversion efficiency of optical modulators and photodetectors directly impact the performance of photonic links and beamforming architectures as they determine the effective RF gain and noise figure of the photonic block of the antenna beamforming system. Modulators must be able to tolerate large input optical powers and provide adequate linearity so to facilitate adequate dynamic range, as well as realize high modulation efficiency over wide bandwidths. Photodetectors must be able to efficiently convert RF signals modulated on high power optical carriers and do so over adequate bandwidths. There is a great deal of research and development work on the realization of high performance semiconductor based devices that can tolerate the inhospitable environment typical for satellite payloads. These devices are critical wherever photonic structures are implemented (essentially for all proposed architectures) and the successful development of high performance devices will enable the implementation of a wide variety of photically implemented antenna beamforming architectures.

Other passive components such as optical fiber, Bragg gratings (for true time delay), and wavelength combiners for multiple beam multiplexing or optical signal routing will also be necessary for the successful implementation of many of the structures that will be enabling for future SATCOM antenna systems.

5. CONCLUSION

In conclusion, our work has focused on the determination of beamforming architectures that can leverage photonic technologies to enable the implementation of next generation SATCOM antenna systems. Photonics can enable the use of many beams, wide bandwidths, and low size, weight, and possibly power to facilitate the implementation of next generation, low cost, spaceborne communications networks and architectures.

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