An adaptive, agile, reconfigurable photonic system for managing analog signals

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ABSTRACT

Photonic techniques can be applied to microwave and millimeter wave transmission and signal processing challenges, including signal transport, distribution, filtering, and up- and down-conversion. We present measured performance results for a wideband photonic-assisted frequency converter with 4 GHz instantaneous bandwidth and full spectral coverage up to 45 GHz. The photonic-assisted converter is applicable for both ground and space applications. We show the system performance in a ground station application, in which high frequency analog signals were transported over a moderate distance and down-converted directly into a digitizing receiver. We also describe our progress in the packaging and space qualification of the photonic system, and discuss the next steps toward higher TRL. The photonic system provides an adaptive, agile, reconfigurable backbone for handling analog signals, with performance superior to existing microwave systems.

1. INTRODUCTION

Analog signal processing is an essential part of modern satellite systems. A received signal from an antenna may contain digital or analog information, and it may ultimately be processed digitally, but unless the signal can be digitized directly—a challenging prospect as the frequency of the signal increases—there will be some amount of analog signal processing required. This may include amplification, filtering, transmission over some distance, distribution to multiple receivers/transmitters, and frequency conversion for up- or down-conversion. RF and microwave components are very mature, and a baseline level of performance has been demonstrated for all of these processing functions. Demand for capacity and the broader use and congestion of the electromagnetic spectrum are among the forces increasing the complexity, cost, and performance requirements of analog systems. As higher levels of performance and higher carrier frequencies become required, especially in the millimeter wave portion of the spectrum, new approaches are needed to meet the challenges. Photonics offers some compelling advantages on this front: bandwidth; size, weight and power (SWaP); linearity; and frequency agility; providing a reconfigurable infrastructure for analog signal processing.

Photonic systems can cover a wide frequency range and instantaneous bandwidth (IBW), with frequency ranges extending to millimeter waves and IBW as large as 4 GHz or more. Optical fiber provides an exceptionally low loss transmission medium, with roughly 0.2 dB/km loss regardless of the analog frequency it's carrying. Wavelength division multiplexing can further extend bandwidth by allowing multiple signals to share the same path.
The SWaP of a photonic system can be relatively low due in part to the wide bandwidth of the system: a single set of hardware can cover many decades of the RF spectrum. Optical fiber is also substantially lighter in weight than coaxial cable, and its inherent immunity to electromagnetic interference reduces the amount of cost, effort and space required for shielding.

The linearity of a system is especially important when distortion effects will limit performance. Traditional RF and microwave components in a congested RF spectrum can lead to severe signal distortion. With photonic components, the nonlinearities are different, and these differences can be applied in ways that surpass the performance of traditional approaches. One example is the suppression of MxN mixing spurs for wideband frequency conversion [1].

The ability to rapidly tune a system over wide frequency ranges opens up the useable spectrum, enabling a frequency agile system. A photonic system's frequency range is usually set by either the electro-optic modulator or the photodetector. For each of these components, COTS solutions exist extending well into the millimeter wave region of the spectrum. Tuning the wavelength of a laser can provide quick access to any portion of the spectrum within the range of these components.

The wide bandwidth and large frequency range of a photonic system provides a flexible, high frequency backbone that can adapt to changing missions. Such a reconfigurable system can enable flexible architectures, reduce the cost of ownership, and adjust to changing environments.

2. PHOTONIC FREQUENCY CONVERSION

A conceptual description of a photonic frequency converter is shown in Figure 1 [ref]. Light from a continuous-wave (CW) laser is amplified and then split along two paths. On the upper path, the light is modulated by a signal from an antenna so that signal sidebands are produced on either side of the optical carrier. An optical bandpass filter, implemented here by a polarization-maintaining (PM) optical circulator and tunable fiber Bragg grating, selects one of the two sidebands and passes it to a directional coupler. On the lower path, the light is modulated by a local oscillator (LO) signal. One of the LO sidebands is selected by the optical bandpass filter and sent to the directional coupler, where it combines with the signal sideband from the upper path. At the balanced detectors, the combination of these sidebands produces an intermediate frequency (IF).

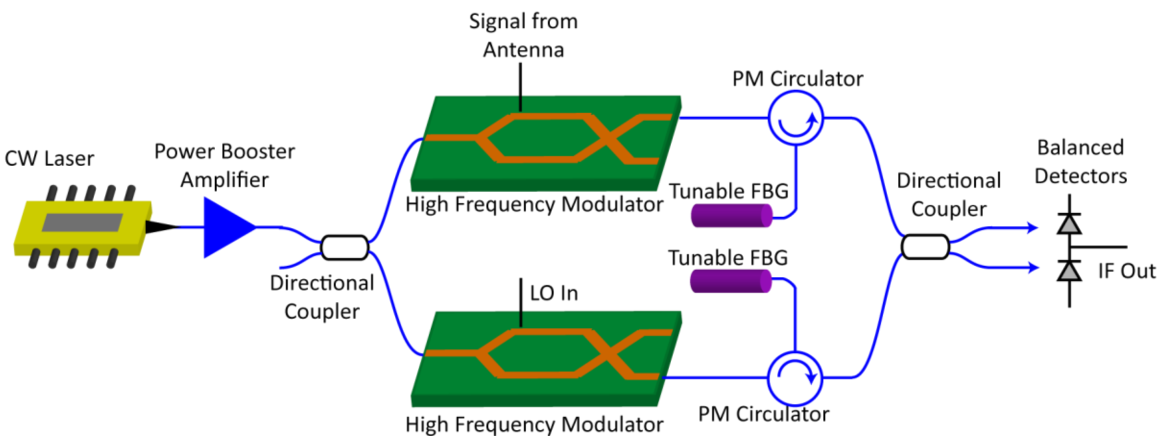
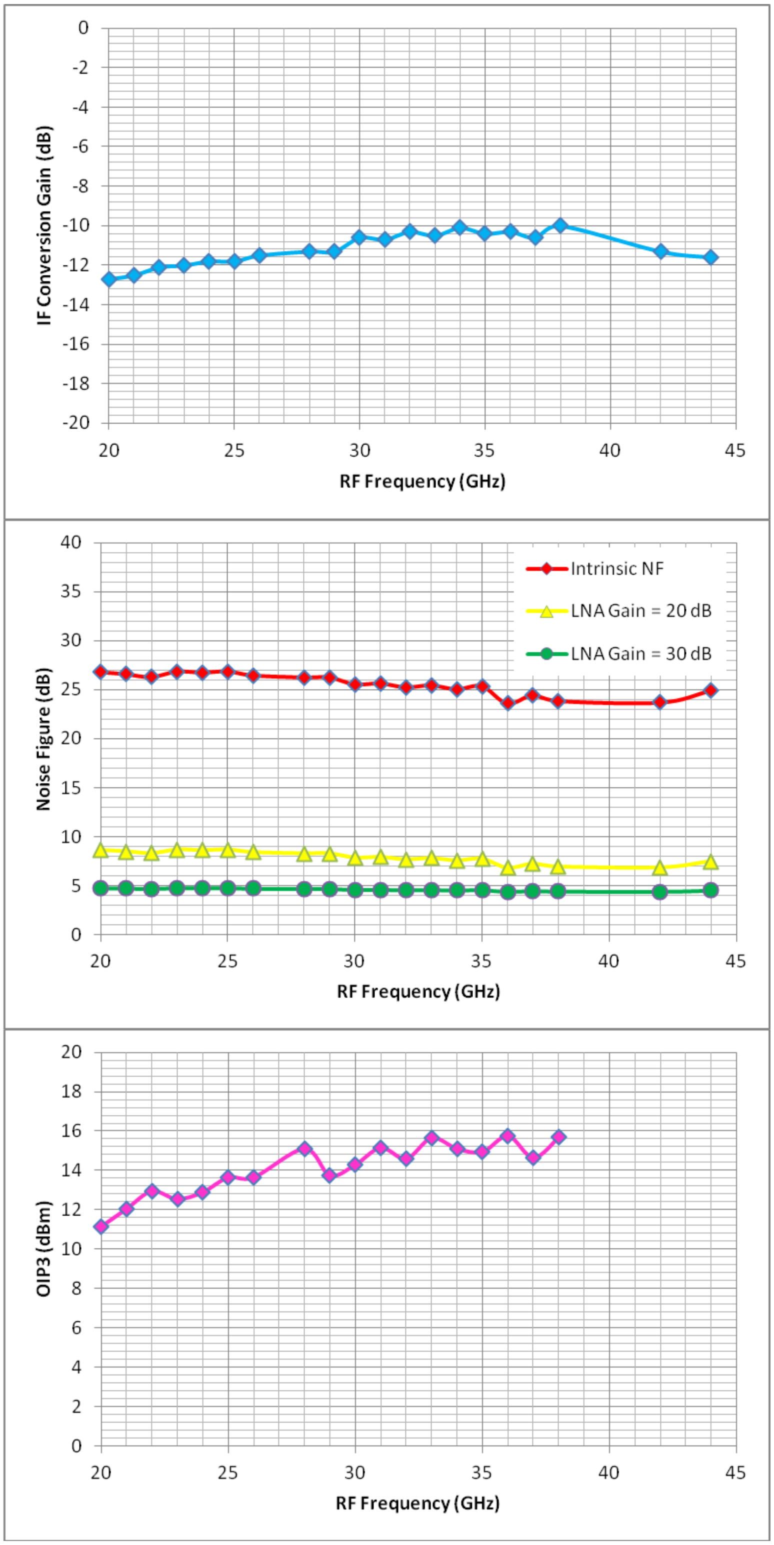


Figure 1. Photonic frequency converter block diagram.

Performance of the photonic frequency converter was measured from 20 - 45 GHz and is shown in Figure 2. The conversion gain measurement shows, without any compensation, ± 1.5 dB of ripple across the entire band. In addition, across any 4 GHz the ripple is less than ± 0.9 dB. Noise figure is also relatively flat across the band. To show the effect of the photonic frequency converter noise figure in a system context, the noise figure is also shown with an LNA at the input to the photonics, assuming a 4 dB LNA noise figure and showing the impact of different levels of LNA gain: 20 dB and 30 dB. Anomalies in the test equipment at higher frequencies limited our ability to obtain some of the data. For example, OIP3 measurements stop at 38 GHz because we were unable to distinguish between spurs from the signal sources and those from the photonic system at higher frequencies.



(a)

(b)

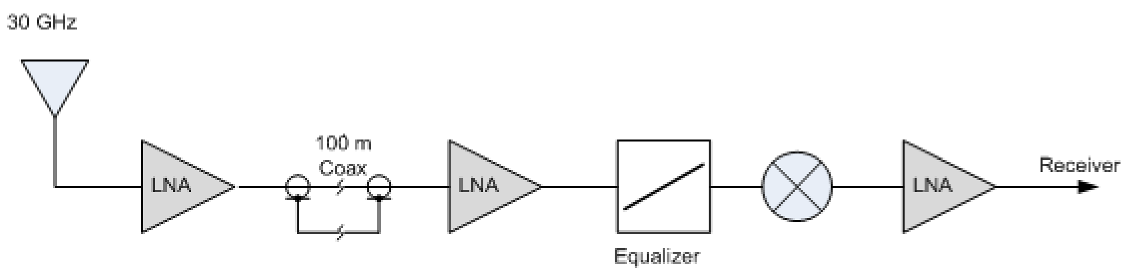
(c)

Figure 2. Measured results for the photonic frequency converter: (a) IF conversion gain, (b) intrinsic noise figure along with cascaded noise figure with a 4 dB NF LNA at the photonic tuner input and LNA gain values of 20 dB and 30 dB, and (c) output 3rd order intercept point (OIP3).

3. GROUND STATION CASCADE EXAMPLE

It would be misleading to compare the performance of the photonic frequency converter directly to an RF mixer, since the photonic frequency converter also includes or replaces other portions of an RF system, such as coaxial cable lengths and equalizers. The value of the photonic frequency converter is best understood in the context of a specific system. Consider an example in which a 30 GHz analog signal must be delivered to a digital receiver at an intermediate frequency (IF) of 1 GHz, with a gain level of 30 dB and over a distance of 100 meters. Five approaches to such a link are shown in Figures 3-7.

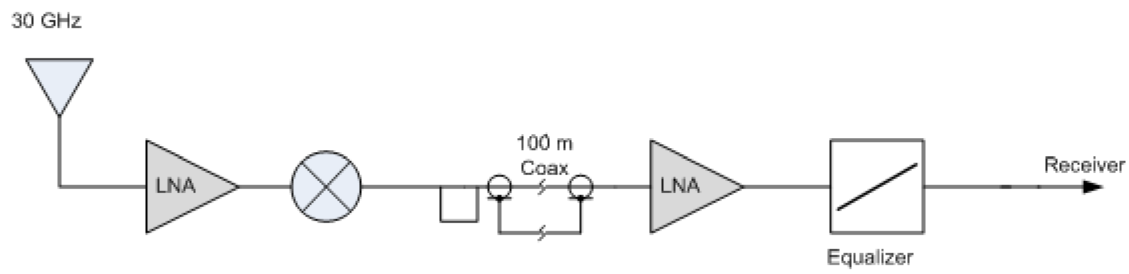
Figure 3 shows a relatively straightforward link design: the 30 GHz signal goes through a low-noise amplifier (LNA), then travels over a 100-meter length of coaxial cable to a base station, where it sees another Ka band amplifier, an equalizer to compensate for the frequency-dependent loss of the cable, an RF mixer to convert the signal down to the IF, and an L band amplifier to get the appropriate amount of system gain. For an instantaneous bandwidth of 500 MHz, the cascade analysis of these components yields a minimum detectable signal (MDS) of -74.1 dBm, a spur-free dynamic range of 44.5 dB, and a 1 dB input compression power (P_{1dB}) of -14.4 dBm. These results will serve as a baseline against which the other four link configurations will be compared.



	LNA 1	100 m Cable	LNA 2	EQ	Mixer	IF LNA	Total
Gain	29.4	-28	15.6	-8	-8	29	30
NF	6.6	28	3	8	8	3	12.9
OIP3	23	200	30	200	17	30	22.7
Out P_{1dB}	15	200	20	200	8	20	15.6

Figure 3. 30 GHz RF link with mixer after 100 m coax cable length.

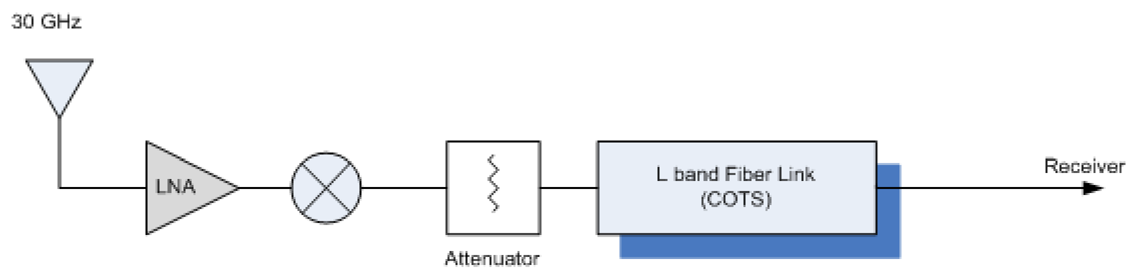
Figure 4 shows an alternative link design: the 30 GHz signal goes through an LNA and is then down-converted to the IF before being sent over the 100 m coaxial cable length, after which it is amplified and equalized. This approach provides a substantial improvement to MDS, since moving the RF mixer ahead of the cable leads to much lower cable loss. The SFDR is slightly degraded, but the main penalty is the large reduction in input compression power, which corresponds to a reduction in system dynamic range.



	LNA 1	Mixer	100 m Cable	IF LNA	EQ	Total
Gain	29.4	-8	-10	31.1	-12.5	30
NF	6.6	8	10	3	12.5	6.7
OIP3	23	17	200	30	200	16
Out P_{1dB}	15	8	200	20	200	7.5

Figure 4. 30 GHz RF link with mixer before 100 m coax cable length.

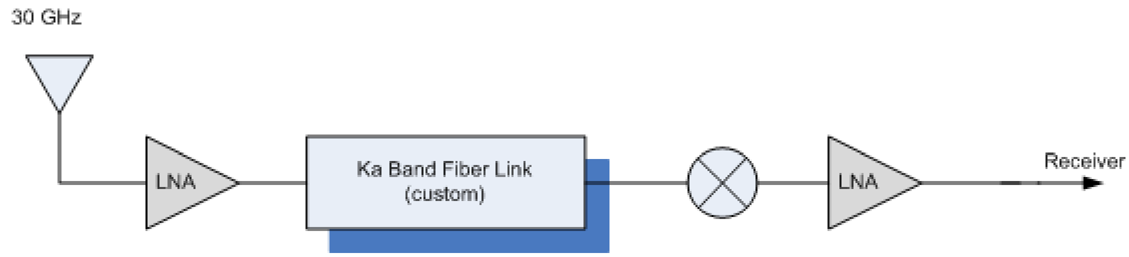
In the link configuration shown in Figure 5, the signal is down-converted at the antenna as in Figure 4, but the coaxial cable is replaced by a COTS L band fiber optic link. Since the fiber link has positive gain, an attenuator is needed to set the system gain level correctly. This configuration yields performance on nearly the same level as the baseline link.



	LNA 1	Mixer	Attenuator	L Band Fiber Link	Total
Gain	29.4	-8	-20.4	29	30
NF	6.6	8	20.4	12	12.3
OIP3	23	17	200	25	19.9
Out P_{1dB}	15	8	200	15	15

Figure 5. 30 GHz RF link with mixer before 100 m fiber link.

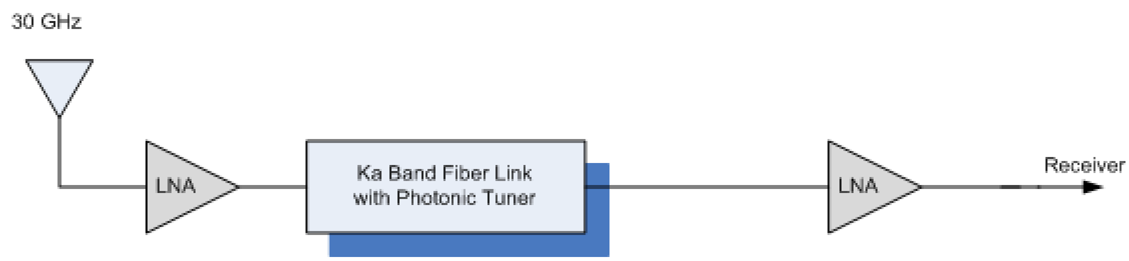
Figure 6 shows a link similar to the baseline link shown in Figure 3, except that the coaxial cable is replaced by a Ka band fiber link. This custom Ka band fiber link is based on measured performance results obtained at Harris. This approach shows significant improvement in both MDS and SFDR, and no degradation to the input compression power. It requires the RF mixer, which becomes the performance limiting component for MDS and SFDR. The input compression power is limited by the LNA after the antenna.



	LNA 1	Ka Band Fiber Link	Mixer	IF LNA	Total
Gain	29.4	-19	-8	27.6	30
NF	6.6	30	8	3	8.3
OIP3	23	8	17	30	21.5
Out P_{1dB}	15	-2	8	20	15.6

Figure 6. 30 GHz Ka band 100 m fiber link with mixer at receiver.

The final configuration is shown in Figure 7, in which the 30 GHz signal is amplified by the LNA and then converted to an optical signal, transmitted over 100 m of optical fiber, and down-converted using the photonic frequency conversion technique described above. Using the measured values of the photonic frequency converter from the previous section, we see that this approach provides the best overall performance and incorporates all of the advantages of photonics discussed in this paper.

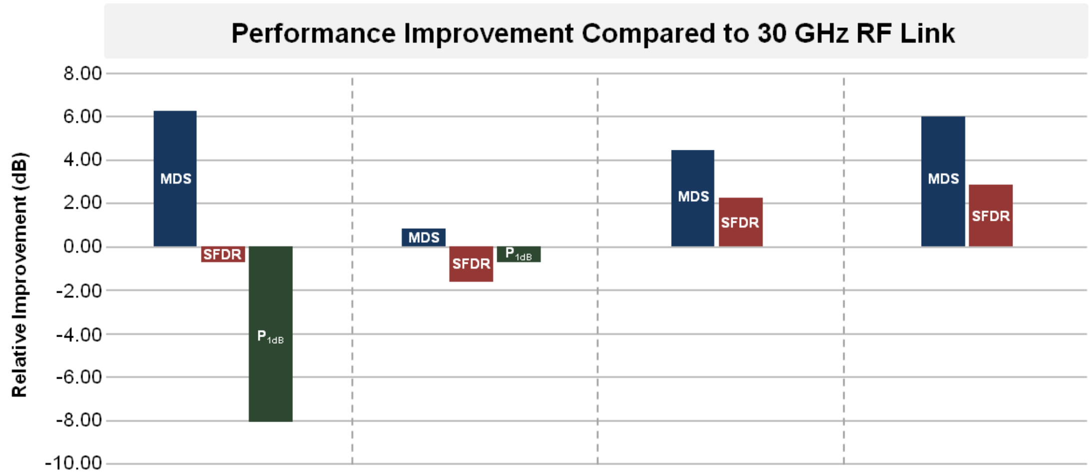


	LNA 1	Ka Band Fiber Link with Photonic Tuner	IF LNA	Total
Gain	29.4	-10.6	11.2	30
NF	6.6	25.6	3	7
OIP3	23	14.3	30	20.9
Out P_{1dB}	15	5	20	15.6

Figure 7. 30 GHz Ka band 100 m fiber link with photonic tuner.

The cascade analysis results for each of these configurations are summarized in Table 1, where each link is compared to the baseline link (Figure 3) in terms of MDS, SFDR, and input 1 dB compression.

Table 1. Summary of cascaded link performance compared to 30 GHz RF link.



	RF Mixer at Antenna, L band Coax Link	RF Mixer at Antenna, L band Fiber Link	30 GHz Fiber Link, RF Mixer at Base Station	Photonic Mixer
MDS	6.21	0.60	4.63	5.96
SFDR	-0.29	-1.47	2.28	2.77
P_{1dB}	-8.10	-0.60	0.00	0.00

4. PACKAGING EFFORTS AND SPACE QUALIFICATION

The photonic components that comprise the photonic frequency converter are widely used in other photonic systems. We combined these components onto two PCI-style cards, with the goal of integrating them in a chassis for a reconfigurable payload, such as the AppSTAR™ system developed by Harris Corporation [ref]. The results of this packaging effort are shown in Figure 8. This same hardware was used to produce the measured results shown in Figure 2.

Some initial efforts were made to investigate space qualification of the photonic frequency converter and are broadly summarized in Table 2. An examination of results compiled in the NASA GSFC database summary of radiation effects on optical fiber [3] and discussions with component vendors form the basis for this assessment. Future efforts will ensure a fully space-qualified photonic frequency converter.

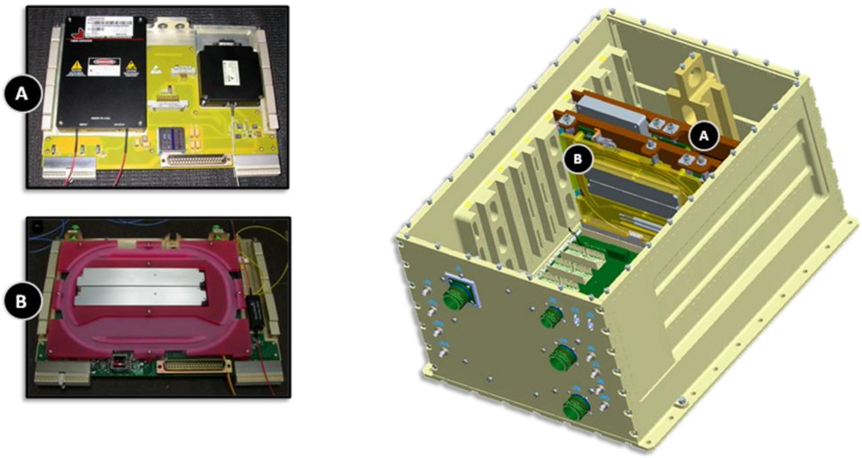


Figure 8. Photonic frequency converter hardware, assembled on PCI cards for integration in a reconfigurable space payload.

Table 2. Initial look at space qualification of components for the photonic frequency converter.

Component	Radiation	Temperature	Shock	Vibration
Laser	● (dark green)	● (dark green)	● (dark green)	● (dark green)
EDFA	● (yellow)	● (yellow)	○ (white)	○ (white)
FBG Filter	● (yellow)	● (dark green)	● (dark green)	○ (white)
Photodetector	● (dark green)	● (dark green)	● (dark green)	● (dark green)
Modulator	● (dark green)	● (dark green)	● (dark green)	● (dark green)
PM Fiber	● (dark green)	● (dark green)	● (dark green)	● (dark green)
Splitter/Coupler	● (dark green)	● (dark green)	● (dark green)	● (dark green)
Circulator	● (dark green)	● (dark green)	● (dark green)	● (dark green)

5. CONCLUSION

Photonic frequency conversion can enhance the performance of microwave and millimeter wave systems by eliminating transmission loss in coaxial cable, simplifying cable routing and management, supporting multi-beam architectures, expanding the useable spectrum, increasing system bandwidth, reducing SWaP, improving linearity, and providing frequency agility. Measured performance results for Ka band show the potential for system-level performance improvements. Applications in both ground and space systems are envisioned, and a space-qualified photonic frequency converter system is not far away.

6. REFERENCES

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2 Beadle, E.R. and Dyson, T., Software-Based Reconfigurable Computing Platform (AppSTAR™) for Multi-Mission Payloads in Spaceborne and Near-Space Vehicles, ERSA Conference Keynote Address, 2012.

3 Ott, M.N., Radiation effects data on commercially available optical fiber: database summary, IEEE Radiation Effects Data Workshop, 2002.