Imaging RF Phased Array Receivers using Optically-Coherent Up- 
conversion for High Beam-Bandwidth Processing

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Abstract: This paper will present a novel optical up- 
conversion technique for RF phased array receivers that 
uses a spatially coherent read-out approach, which offers 
unlimited beam-bandwidth processing without the need for 
any digital beam forming. It does so by using an optical 
 lens to perform an inverse spatial Fourier Transform on 
the up-converted RF signals, thereby rendering a real-time 
image of the RF environment. In so doing, this approach 
offers spatial isolation between signals received over 
various angles-of-arrival and thereby not only improves 
signal-to-noise ratio but also renders the receiver less 
vulnerable to jamming.

Keywords: RF photonics; fiber optics; imaging; phased 
array; beamforming; beam-space; communications.

Introduction

Conventional radio-frequency (RF) receivers usually take 
one of several basic forms: an omnidirectional receiver 
whose antenna captures signals from all directions; a 
highly directional receiver with a dish-like antenna 
designed to capture signals only from a particular 
direction selected by mechanically reorienting the dish; or 
a phased array, which coherently combines inputs from a 
distribution of low-directionality antenna elements within 
an aperture, producing a beam that can be steered over a 
wide range by adjusting the relative phases of the 
elements. Advanced phased arrays can also perform more 
sophisticated beam forming, yielding multiple 
simultaneous beams or other engineered beam patterns.

There are two general approaches to array-based beam 
forming: digital and analog. In digital beam forming 
(DBF) an array of RF channels receives the desired 
signal, each comprising an RF chain that may include 
multiple low-noise amplifier (LNA) stages, filter(s), 
oscillator(s), mixer(s), and an analog-to-digital converter 
(ADC). Once digitized, the outputs from all channels are 
fed to a digital signal processor (DSP) to render a spatial- 
spectral map of the RF environment. In this approach, 
performance is affected by the inherent 2nd and 3rd order 
nonlinearities of the RF chain components, that generate 
intermodulation spurs. This, in turn, gives rise to spectral 
regrowth that ultimately limits the extent to which one 
can achieve spatial-spectral orthogonality. Additionally, 
quantization errors that arise in the ADC, which are 
inherent in DBF systems, impose a lower bound on the 
noise floor. To overcome the limitations in DBF systems, 
phased-array analog beam combiners can be used, which 
use phase shifting and transmission-length adjustment to 
perform spatial beam forming. Such analog beam 
combiners come with the cost of significantly limiting the 
number of beams that can be formed simultaneously and 
narrowing the operational bandwidth.

An alternate approach that combines the advantages of 
DBF and analog beam combiners is to use a lens-based 
antenna that offers the ability to perform analog beam 
forming, or imaging [1,2]. Various implementations of 
lensed antennas include Luneburg [3], Rotman [4,5], and 
zoned lenses [6], and more recent work in beam-space 
MIMO applications [7,8]. However, with the use of lens 
antennas come practical limitations: in the case of 
Luneburg lenses, their size and weight limit their 
usefulness for many applications; with zoned lenses, there 
are fundamental limits in diffraction efficiency [9], which 
can give rise to crosstalk between spatial sectors. Also, 
 lens systems scale in three dimensions, meaning that as 
the lens increases in area, there is a concomitant increase 
in focal length. This ultimately limits the ability to reduce 
their form-factor, which can preclude their use in certain 
locations or environments.

From the discussion above, it appears that an ideal beam 
forming system would include an analog front end, such 
as beam combiner or lens antenna, to minimize 
quantization errors and nonlinearities, but still offer the 
extremely agile beam forming of DBF along with the 
form-factor of a phased-array antenna.

Our solution is a photonic imaging receiver, a novel type of 
these phased array that uses the coherent properties of 
frequency upconversion in high-performance optical 
modulators to enable analog beam forming, through the 
use of free-space optics (imaging) to perform signal 
correlations between array elements that are 
conventionally performed computationally after signals 
are detected by down-mixing and sampling ADC. This 
approach preserves spatial coherence across the entire 
array and over broad bandwidth.

Imaging Receiver Concept

In the photonic imaging receiver, spatial coherence is 
achieved by using a common laser to feed all channels 
in the array, with each channel containing an ultrawide- 
bandwidth optical modulator connected directly to an
antenna element that upconverts the received RF signal right at the antenna front-end. The output from each antenna element is an optical fiber with the upconverted RF signal now a sideband on the optical carrier. This way, the RF wave front reaching the antenna array is converted to an optical wave front propagating in an optical-fiber bundle. The fiber outputs are then collected into an array whose layout replicates that of the antenna array, albeit at a reduced scale. At this point, the optical sideband containing the RF signal is filtered off the carrier and allowed to propagate in free space. As the filtered output from each fiber expands, the overlapping sidebands, bearing information about the amplitude and phase of every RF signal received by each antenna element, coherently combine to give rise to a spatially-coherent recreation of the RF signal, but in the optical domain.

Having a spatially-coherent, upconverted version of the incident RF wavefront, we can exploit the field of Fourier optics [10], where a single lens performs massive spatial processing, namely an analog Fourier transform (FT), at the speed of light, in parallel, and consuming no power, as illustrated in Fig. 1. The result of the FT is that upconverted RF energy incident from sources at different locations converges to spots at different positions in the image plane. Sources are thereby spatially separated prior to their detection, which minimizes their intermixing. Further, any spurs that result from intermodulation in the front-end (the optical modulator and low-noise amplifiers (LNAs) behind the antennas) will be offset spatially in the image plane, and thus will not impinge on the same detector as the primary signal, further mitigating their impact on the receiver’s performance.

The system as described thus far is a broadband passive RF imager [11], whose unique capability is the spatial separation of signals via optical processing. What distinguishes the imaging receiver presented here from a mere imager is the ability to recover signal waveforms with sufficient fidelity for applications such as wireless communications, and radar. The imaging receiver accomplishes this through the use of a coherent optical LO for downconversion. This optical LO is offset in frequency from the laser that drives the receiver’s upconversion modulators, such that when it is overlaid on a photodiode with the image spot from a source in the scene, a beat tone results at a controllable intermediate frequency (IF), with any signal modulation on the source preserved. At this point the signal can be recovered by ADC at the photodiode output.

The system to generate the coherent tunable optical LO (TOLO) is based on injection locking a second laser to a modulation sideband from the primary laser. The scheme used is that of Ref. [12], except that instead of beating the offset laser with the primary to realize a tunable RF signal source, here we beat the offset laser with the upconverted sideband energy from the received RF signals. Otherwise, the scheme is the same, and provides the same fidelity (IF-downconverted carrier linewidth ~1 Hz, phase noise <105 dBC/Hz @ 10-kHz offset) as indicated in Ref. [12].

Prototype Photonic Imaging Receiver

We designed and built a system consisting of a 1x8 array of ultra-wideband Vivaldi antennas, with an operational bandwidth of 5-20 GHz, as pictured in Fig. 2(a), and shown schematically on the right in Fig. 2(b). At each antenna feed there is a LNA whose outputs are connected to optical modulators. These are Mach-Zehnder Interferometer (MZI) modulators that have >30 GHz analog bandwidth and offer high carrier extinction of up to 30 dB when properly biased. Carrier extinction in the modulator enables the system to operate more effectively at lower frequencies, where the frequency separation between the upconverted RF energy and the optical carrier is too small to effectively separate them with optical filters alone. Incomplete carrier suppression allows optical energy at the carrier frequency to reach the image plane, which distorts the image and contributes to optical noise at the signal recovery photodiode, but notably it does not interfere with the signal recovered at IF, being separated from the IF by the RF carrier frequency.

Subsequent to the upconversion modulators, the signals pass through a custom fabricated 1x8 array of low-speed optical phase modulators. This modulator array is used to apply beam-forming phase biases to the channels individually, as well as to compensate in real-time for the random phase variations induced by perturbations of the loose optical fibers. (For simplicity, these phase shifting modulators are indicated in Fig. 2(b) simply by the “optical phase shifting” blocks.) An active-feedback process ensures that the optical signals across the array remain spatially coherent [13]. The modulator array output fibers are arranged such that their positions correspond to the antenna positions, replicating their spatial positions at reduced scale. In this manner, the sideband light emerging from the fiber array replicates the RF field at the antenna aperture, scaled up in frequency.

![Prototype Photonic Imaging Receiver](image-url)
From the fiber outputs, the optical signals emerge into the free-space optical processor. There, additional carrier suppression is provided by optical bandpass filters. The light from one sideband passes through the filters and the contributions from all fibers overlap as they propagate. At this point, a lens is used to produce an image of the sideband energy that replicates the RF scene. A beam splitter generates two copies of the image plane. One copy is incident on a camera sensor that is used to display where RF energy is coming from, i.e., angle of arrival (AoA) or spatial sector, as well as the apparent magnitudes of the imaged sources. The second image copy is formed on another linear photo-detector array. These photo-detectors are read out with a 2-stage, AC-coupled transimpedance amplifier (TIA) configuration. The TIA provides signal gain and current-to-voltage conversion (5000 V/A), and suppresses output thermal noise. A TOLO is used to down-convert the sidebands to a suitable IF within the photo-detector bandwidth. The LO is brought into the optical processor through the same 8-fiber array that carries the sidebands. This optimizes overlap of the signal and LO on the detector, at the expense of the contribution of one channel to the image (hence, our 1x8 array becomes in practice a 1x7 array).

Analog waveforms recovered at IF are output from the system via SMA connectors. The eight adjacent photo-detectors can be used to demonstrate simultaneous recovery of independent spatially separated waveforms at the same carrier frequency. Figure 2(b) depicts the experimental setup. Two sources were arranged at ~2.5 m from the imaging receiver, separated by 0.4 m (angular separation 9°). One of the sources consisted of an Agilent E8257C PSG signal generator that produced ~7 dBm (equivalent isotropic radiated power, EIRP) of output power at a carrier frequency of 15.94 GHz. This source (PSG) was modulated using the PSG’s internal baseband signal generator at 50 Mbaud with 16QAM modulation, for a data rate of 200 Mbps. The second source was a high-power photodiode (PD) array driven by a pair of coherent lasers [14] offset in frequency by 17 GHz. One laser was modulated, using single-sideband suppressed carrier modulation, with the output signal from a Tektronix 7000 series arbitrary waveform generator (AWG). The AWG generated a 1.06-GHz signal modulated at 15.36-Mbaud, with 4QAM for 30.72 Mbps data rate. The resulting signal transmitted from this source (AWG-PD) was ~6 dBm EIRP, also at 15.94 GHz.

Results from this experiment are shown in Fig. 3. The figure contains recovered QAM constellations displayed using VSA software running on an oscilloscope, along with 1D images obtained from the camera sensor. From comparing the plots in the 3 columns we see that the independent data signals were successfully recovered simultaneously with minimal degradation (middle column), as compared to the cases when only one source
Conclusions
The results presented here demonstrate the potential of the photonic imaging receiver to enable extreme beambandwidth signal processing by the use of coherent optical upconversion and analog signal processing by Fourier optics. Experimental data show that spectral reuse is possible in communications networks by virtue of extreme spatial sectorization, wherein all spatial sectors are accessible simultaneously.

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