OPTICALLY SMART ACTIVE ANTENNA ARRAYS

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ABSTRACT

A prototype X-band active antenna array with adaptive optical processing is presented. The optical processor, referred to as an auto-tuning filter, is able to extract the strongest principal component in a two-signal space with up to 30dB enhancement with respect to the other signals. The processor is compact (8cm by 4cm) and scalable to a large number of antenna elements and incident RF waves (sources). Three major components of this system are described in detail: (1) the lens antenna array front end with angle-of-arrival pre-processing; (2) the electrooptic modulation and optical carrier suppression stage; and (3) the smart optical processor (auto-tuning filter).

INTRODUCTION

The adaptive processing in smart microwave antenna systems [1] can either be done at the analog front-end at the carrier frequency or after down conversion and analog-to-digital conversion at baseband using digital signal processing (DSP) techniques [2]. Front-end processing is fast, but expensive and complex as the adaptation circuitry requires microwave variable phase shifters and variable gain-control elements. The more common DSP approach reduces system complexity, is more economical, and is more flexible, however it is typically power inefficient, has modest bandwidth, and exhibits relatively slow adaptation speeds. System simplicity is also the driver of optical link technology, which offers a robust means of processing the signals received from the antenna array at an almost arbitrarily remote location.

In this paper, we present an X-band smart antenna array in which the adaptive processing is performed by nonlinear optical circuitry. The optical circuitry finds and extracts the principal components of the input signal space, which means the strongest independent component of the ensemble of signals. In the present case, we use principal component extraction to separate a strong signal from a weaker one. More generally our goal is to show that the use of nonlinear optical techniques can simplify adaptive antenna systems and relieve the computational burden placed on digital signal processing. Furthermore, the optical approach merges well with fiber link technology.

The architecture discussed in this paper is intended to be used for a large number of antenna elements. The initial demonstration uses only two microwave receivers and two test-sources; however, the optical portion does not substantially change as the number of array elements increases.

The prototype system is shown in Fig.1. The front end consists of a 49-element discrete lens antenna array followed by active antenna receivers positioned along the H-plane focal arc of the lens. Each receiver position corresponds to a specific direction of a plane wave incident and received by the lens array. The receivers contain gain control amplifiers in order to balance the two IF channels.

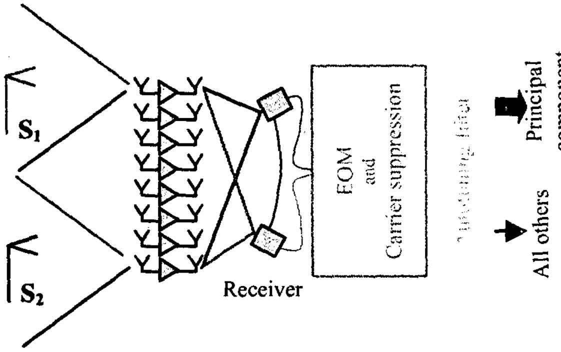

Figure 1. Block diagram of prototype optically smart antenna array. The active receivers are positioned on the focal arc of the discrete lens antenna. The IF signals are then imposed onto the optical beam and processed by the adaptive optical circuit.

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The IF signals are imposed as phase modulation (PM) sidebands on the optical carrier using electrooptic modulation. An adaptive holographic element is used to suppress the optical carrier. The subsequent optical beam, modulated with two signals, is then coupled into a multimode optical fiber connected to an adaptive optical circuit we refer to as an “auto-tuning filter” that separates the two principal components of the signal input space.

We next describe details of the design, operation and measured performance of each of the three components indicated in the system block diagram in Fig.1: (1) the microwave front end; (2) the electrooptic modulation and carrier suppression stage; and (3) the optical processing (auto-tuning filter) stage. In the last section of the paper we discuss the implementation of an extension of the 2-receiver system to an N-receiver adaptive array.

THE MICROWAVE FRONT END ACTIVE ANTENNA

The lens antenna array shown schematically in Fig.1 is a quasi-optical array analogous to a Rotman lens. Such active T/R lenses have recently been demonstrated to improve dynamic range, increase effective radiated power (ERP) by spatial combining, and improve reliability, e.g. [3]. In this work, we initially use a passive discrete lens with 49 patch antenna elements, in which the lensing is accomplished with varying delay lines across the array between input and output antenna elements. The lens has a number of imperfect focal points, and in this demonstration we use two of these points along the H-plane focal arc to place receivers, each preferentially receiving one spatial beam.

Each receiver is an active integrated antenna, the block diagram of which is shown in Fig.2.

A RT/Duroid substrate with a relative permittivity of ε_r=10.5 and 0.508 mm thick is used. The high dielectric constant allowed us to reduce the size of the integrated active antennas. The antennas are designed for 10 GHz (6.3 mm by 4.3 mm), with a bandwidth of about 150 MHz. The antenna feed is connected directly to low noise amplifiers (LNA) for optimal noise figure (CHA2063 United Monolithic Semiconductors, with a 7-13 GHz bandwidth, 16 dB gain and 2 dB noise figure). The output power for the LNAs at 1 dB-compression point is 10 dBm, with low DC power consumption (40 mA at 5 V). A mixer downconverter follows the LNA. The IF amplifiers are CLC522 National Semiconductors wideband variable gain amplifiers and they provide more than 40 dB gain control through a single high impedance voltage input.

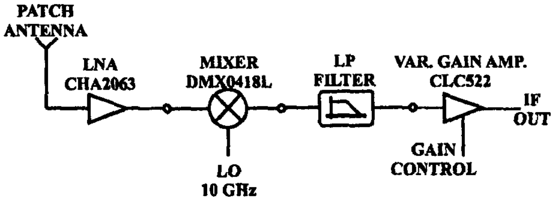

Figure 2. Block diagram of the active receiver unit. The ability to control the levels of the signals is important for proper optical processing.

The ability to control the levels of the signals at the input of the optical processor is very important for proper processing, as discussed below. The output of the IF amplifiers drives cable television driver amplifiers, the outputs of which drive the electrooptic modulators (EOMs).

The test signals are two noise signals filtered to about 100 kHz bandwidths, upconverted to 128 MHz and 130 MHz, and then to the 10 GHz microwave carrier. Power amplifiers boost the signals, which are then transmitted by two horn antennas, copolarized with the patches in the receiving lens array. Even though we use noise signals upconverted into the 100 MHz range, note that the optical processor can process higher bandwidth signals. Furthermore, the IF signals could share the same spectrum. (The reason that we use two signals at the different IF frequencies is ease of measurement.)

ELECTROOPTIC MODULATION AND CARRIER SUPPRESSION

The IF signals are encoded as phase-modulation sidebands on an optical carrier using a *single* electrooptic crystal modulator as shown in Fig.3: the optical beam passes through a magnesium doped lithium niobate crystal with an array of microstrip electrodes. This beam is therefore both spatially and temporally modulated. A prototype with two electrodes has been built.

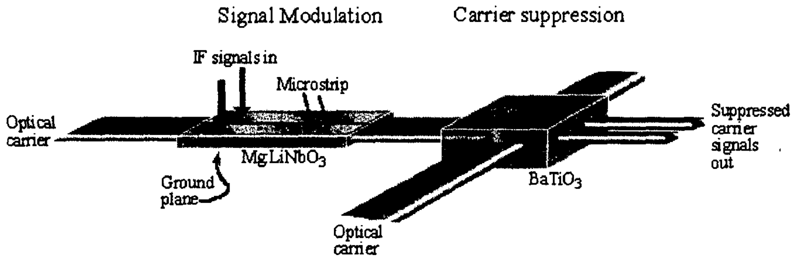

Figure 3. The electrooptic modulator with two microstripe electrodes and the carrier-suppression optical circuit.

Before entering the optical processor (auto-tuning filter), the carrier needs to be suppressed so as not to introduce false signal correlation. This is accomplished through two-beam coupling inside a barium titanate photorefractive crystal. Two-beam coupling is a non-linear process, which allows one optical beam to give energy to the other one via an index grating in the photorefractive medium. With the purpose of carrier suppression, this interaction takes place between two beams coming from the same laser source, one of which has been modulated with the IF signals by the EOM described above. As a result of this the IF sidebands are transmitted through the crystal, while the carrier is transferred in the direction of the unmodulated beam [4].

The amount of carrier suppression provided by the optical circuit is a function of the intensity ratio of the two beams inside the crystal, the two-beam coupling gain and the phase modulation depth of the modulated beam. The carrier suppression system has been built and characterized. With an intensity ratio between the two interacting beams close to one, a maximum carrier suppression of about 62dB has been measured for a phase modulation index of 0.12.

AUTO-TUNING FILTER

The auto-tuning filter is a self-organized system that extracts the principal component of the input signal space. The filter has one input and two outputs. The input consists of multiple IF signals imposed on an optical beam as described above. One output (# 1 in Fig. 4) provides the strongest IF principal signal component and the other (# 2 in the same figure) provides all the other components. The output of interest depends on the application: for example in case of a weak signal and a strong jammer, *output 2* extracts the wanted signal. In case of a signal barely above noise level,*output 1* delivers the signal with suppressed noise [5]. An illustration of the design of the auto-tuning filter is shown in Fig. 4. It is fundamentally an optical oscillator where gain is supplied by photorefractive two-beam coupling. There are two loops in the oscillator: the gain loop, which includes the two photorefractive crystals; and the reflexive loop, which incorporates only one of the crystals.

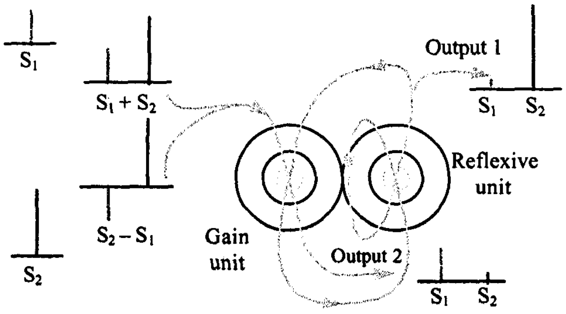

Figure 4. Schematic diagram of the auto-tuning filter. The strongest independent component of the ensemble of input signals is extracted.

In the interaction that is taking place in the crystal of the gain unit (left crystal of the filter in the figure) the strong input beam yields energy to the oscillating beam. The interaction that takes place in the second crystal is a version of reflexive coupling: one initial beam is split in two unequal parts that are then two-beam coupled. If the optical beam is carrying statistically independent RF signals, the dynamics of reflexive coupling is such that the gain experienced by each RF optically-carried IF signal is proportional to its power (*output 1*). Thus, the stronger the signal, the more gain it undergoes. The gain loop provides feedback to the reflexive-coupling unit, enhancing the competition for gain until the signal that was initially the strongest dominates the oscillation in the loops. In Fig. 4 *output 1* provides the oscillation signal, while *output 2* has the stronger signal suppressed.

The auto-tuning filter was designed, built and then characterized with narrow-band test signals at about 80 MHz, with the two signal frequencies differing by less than 1 kHz. Two acoustooptic modulators (AOs) provide the frequency modulation of a diode-pumped frequency-doubled Nd:YAG laser beam (532 nm). Although AOs have the drawback of being narrow-band devices, they offer the advantage of providing modulated signals without the carrier. It was therefore possible to test the optical processor separately from the carrier suppression circuit. The signal-bearing light from each of the two modulators is launched into a common multimode fiber that is connected to the auto-tuning filter.

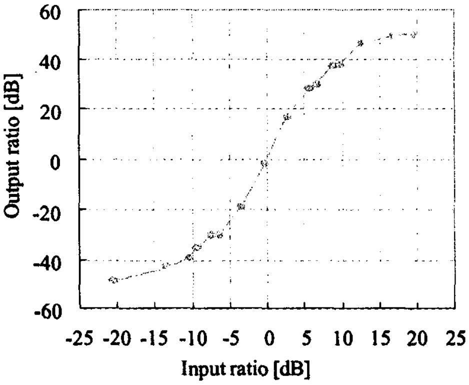

Figure 5. Measured signal enhancement provided by the auto-tuning filter. We define signal enhancement as the power ratio of the two signals at the output divided by their power ratio at the input

The curve displayed in Fig. 5 shows the signal enhancement provided by the auto-tuning filter. We define signal enhancement as the power ratio of the two signals at the output divided by their power ratio at the input. The interesting region of this plot is the slope around the origin: when the input signals are exactly equal in power, the filter cannot choose one or the other; but as soon as the input ratio differs from 0 dB, the filter becomes capable of extracting the stronger one. For instance, an input ratio of 1 dB produces a 7 dB ratio at the output, providing an enhancement of 6 dB.

The signal processing bandwidth of the photorefractive auto-tuning filter is determined by the oscillator's round-trip path length. Through the use of fiber optics and spherical photorefractive crystals we have developed a filter that measures 8 cm by 4 cm and therefore has a bandwidth of about 0.5 GHz.

DISCUSSION

The prototype presented in this paper is a proof of principle demonstration and therefore uses the minimum number of sources and signals (receivers) to assess its performance. Nevertheless none of the three major components of the system are limited by these numbers. An N-element lens array can be followed by up to N receiver positions along its focal surface. The electrooptic modulator then requires an array of N microstrip lines. The optics otherwise remains entirely the same. The goal of future work is to demonstrate a two-dimensional optically smart active antenna array.

ACKNOWLEDGEMENTS

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