OPTICAL CONTROL OF PHASED ARRAY ANTENNAS: A EUROPEAN PERSPECTIVE

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ABSTRACT

The savings in mass and bulk in phased array antennas resulting from the replacement of microwave element feeds with optical fibre feeds are now widely recognised. However, the technological difficulties in implementing such systems are only now beginning to be addressed. In this paper we review current European work on optical feeds, ranging from systems demonstrator work on optical signal distribution networks to research studies on phased array beam formers using coherent optical techniques.

INTRODUCTION

Work on optically controlled microwave systems has been under way in Europe for over 15 years. The attraction of reduced mass in optical fibre transmission systems for phased array antennas has led to particularly strong interest for space applications. Packaged optical fibre for space applications can have a mass of 0.8 g m^{-1} [1] compared with 40 g m^{-1} for a typical microwave coaxial cable.

In this paper we review examples of recent European work on optically controlled phased arrays, ranging from system demonstrators to speculative research work.

INTENSITY MODULATION/DIRECT DETECTION SCHEMES

Optical signal distribution schemes using intensity modulation and direct detection allow the benefits of optical fibre distribution to be obtained with minimum additional circuit complexity. However, difficult problems of noise, distortion and electrical/optical conversion efficiency have to be solved in order to meet phased array systems requirements [1,2]. Recently, externally modulated optical sources have been realised which have an output power of over 1 mW ex-fibre at modulation frequencies of up to 20 GHz [3]. Using a DFB laser, hybrid-integrated with the integrated optical modulator, relative intensity noise levels of better than -145 dBc Hz^{-1} have been maintained across a 2-20 GHz modulation bandwidth.

Figure 1 shows a signal distribution system developed by Marconi Space Systems in collaboration with GEC Marconi Research Centre for the European Space Agency Advanced Synthetic Aperture Radar demonstrator programme. Since the maximum aperture dimension is of the order of 20 m the array must be folded for launch, and the provision of phase-stable flexible joints would add to the mass penalties of a distribution scheme using electrical transmission. A scheme using optical fibre transmission for both transmit and receive signals was therefore selected.

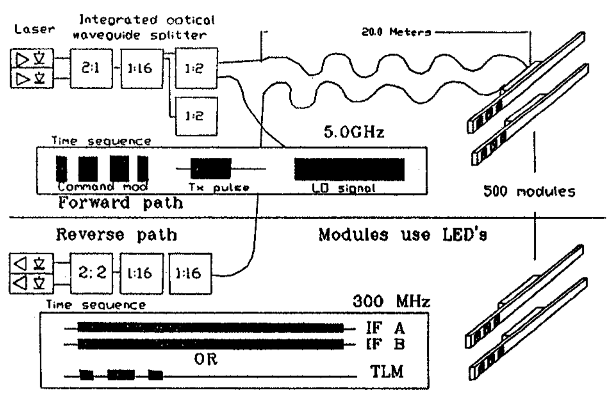

Fig. 1: Optical signal distribution system for space-based synthetic aperture radar.

The demonstrator comprises a subset of a 20 x 2 m array transmitting at 5.3 GHz and using distributed transmit/receive (TR) modules at the array face. Signal distribution is by randomised star networks so that a fibre failure does not produce failures in adjacent array elements.

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Forward Path

Three types of signal are conveyed to each element using a time division multiplex scheme. During transmission a linear frequency modulated pulse with a bandwidth of up to 40 MHz on a 5.3 GHz carrier is distributed. During reception a 5.0 GHz local oscillator signal is distributed. In the interpulse period a 10 μs long 10 MBaud digital signal for element control is modulated on to a 5.0 GHz carrier and distributed.

In the current demonstrator a directly intensity modulated semiconductor laser source of 1 mW output power at 1.3 μm wavelength is used. The output is split successively by 2 and 16 way integrated optical splitters to provide 32 output channels. The initial split allows a flight system to have a cold redundant laser attached to the unused port. Single mode fibres, which can be up to 30 m long, connect the splitter outputs to the TR modules, where the signal is detected by PIN photodiodes and amplified.

The link margins of such a system allow one laser to drive 32 elements with sufficient margin to allow for space radiation damage and gain changes in the components. The phase stability of fibre components, which is particularly important in synthetic aperture radar systems, is superior to comparable coaxial systems and the distribution system loss is much lower. However, losses in optical modulation and demodulation remain an important problem. In the demonstrator the primary power requirement in the TR module is about 220 mW. Performance measurements on the forward path gave a signal output level of 0 dBm, with a noise spectral density of - 115.5 dBm Hz^{-1} over the frequency range 4.98 to 5.33 GHz, resulting in a signal to noise ratio in 60 MHz bandwidth of 37 dB.

Return Path

The return path has two requirements which are non-simultaneous. The first is to pass two channels, each having a bandwidth of 50 MHz centered on 300 MHz, representing the IF returns of the dual polarisation receiver. For each of these channels it is necessary to sum all 512 element signals. The second requirement is to provide a telemetry output from each TR module comprising a baseband signal of rate 20 kBaud.

The return path generator within the TR module comprises two similar sources directly modulated by either a 300 MHz IF signal or the baseband telemetry signal. The sources for the two polarisations have different wavelengths, one being at 0.83 μm and the other at 1.3 μm. The source optical power requirement of 20 μW allows an edge emitting light emitting diode (ELED) to be used. Source outputs are combined in an optical wavelength division multiplexer (WDM) and the signal passed through a 20 m long multi- mode fibre to an initial 16:1 integrated optical combiner. Its output passes to a further 16:1 combiner followed by a 2:2 coupler. The outputs drive dual redundant WDMs with avalanche photodetectors and amplifiers.

Return path measurements for a 512 module system gave an output signal level of - 20 dBm with a noise spectral density of -136 dBm Hz^{-1} over a 60 MHz bandwidth centered on 300 MHz, resulting in an analogue signal to noise ratio of 38 dB (60 MHz) bandwidth and a telemetry bit error rate of 1 x 10^{-7}.

OPTICAL BEAM-FORMING SYSTEMS

A logical extension of the optical signal distribution system described in the previous section is to carry out the phase-shifting operations for antenna beam-forming within the optical distribution network. Two distinct approaches exist: non-coherent beam forming, in which microwave intensity modulated optical signals are subject to differential delay to form the beam- the path length differences being related to the microwave wavelength, and coherent beam-forming in which coherent optical detection translates a phase shift at the optical frequency to a microwave phase shift. These will be considered in turn.

Non-coherent Beam-forming

Conceptually, the most straight-forward optical beam-forming technique is to introduce switched optical delays into the feed path to each element. The main technological challenge with such an approach lies in fabricating electronically operated optical switches with low optical loss: a four bit phase-shifter would have a loss of about 7 dB if implemented in currently available lithium niobate technology [4]. This would reduce the number of elements that can be driven from a single optical source at given receiver-limited signal to noise ratio by a factor of 25.

At University College London a novel optical beam-forming technique, which permits beam scanning at constant radiated frequency, is being investigated. A one-dimensional version is shown in Figure 2. The beam-forming network is in two parts. Network A is dispersive; the fibre lengths are chosen with length increment n Δl such that Δl is an integral number of wavelengths at the boresight frequency $f_1 = f_b$. In the simplest implementation Network B comprises optical paths of equal length and is thus non-dispersive. The outputs of the

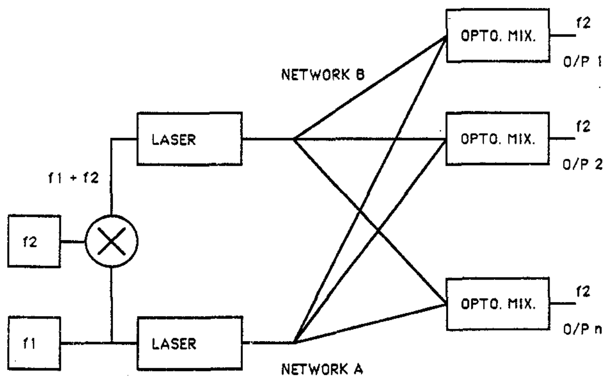

Fig. 2: Non-coherent optical beam-forming technique.

two networks are combined in opto-electronic mixers. These may be either conventional photodetectors followed by non-linear mixing elements or optically pumped mixers [5].

The networks are driven by intensity modulated sources, shown as directly modulated semiconductor lasers in the figure. Two modulation sources are used. f_1 determines the phases at the beam-former outputs, while f_2 determines the output frequency. If Δl is chosen as

$$\Delta l = \frac{m\, v_p}{f_b} \qquad \text{---(1)}$$

where m is an integer and v_p is the phase velocity in the fibre, the modulated inputs to the opto-electronic mixers from Network A will be in phase for $f_1 = f_b$. If the path lengths to each output are equal in Network B the outputs from the mixers will also be in phase. If f_1 is now changed to $f_1 = f_b + \Delta f$ the phase difference between output 1 and output n will be

$$\Delta\phi = \frac{2\, n\, \pi\, m\, \Delta f}{f_b} \qquad \text{---(2)}$$

where the boresight frequency phase difference of 2 n m π is neglected. Because Network B supplies a signal modulated at frequency $f_1 + f_2$ to the opto-electronic mixers the beam-former output frequency, f_2, is independent of f_1 and hence of scan angle.

Coherent Beam-forming

Consider two optical signals, $E_0 = E_{0p} \sin \omega_0 t$ and $E_1 = E_{1p} \sin(\omega_1 t + \phi)$ where E is the electric field, ω the optical frequency and ϕ a phase constant. When the two signals are combined and illuminate a photodetector a term proportional to $E_{0p}E_{1p} \cos((\omega_1 - \omega_0)t + \phi)$ appears in the output current due to the square law nature of the detection process. Thus if $\omega_1 - \omega_0$ is made equal to the desired array output frequency a phase shift at optical frequency can be directly translated to the microwave output.

Plessey Research and Technology and MBB Space Systems are developing proof of concept hardware for such a system for a space-borne phased array operating at 12/14 GHz under a European Space Agency contract. Figure 3 shows in outline the approach which has been adopted. Two optical frequencies with the required offset are differentially phase modulated with the required baseband data before being fed to an integrated optic power splitter. The outputs from this splitter feed individual phase and amplitude modulators for the array elements. Finally the two optical frequency signals are combined on a single polarisation axis and transmitted to the array face by single mode optical fibre. In order to achieve the necessary phase stability it is envisaged that the complete beam forming circuits for a number of elements would be combined as a single integrated optical circuit.

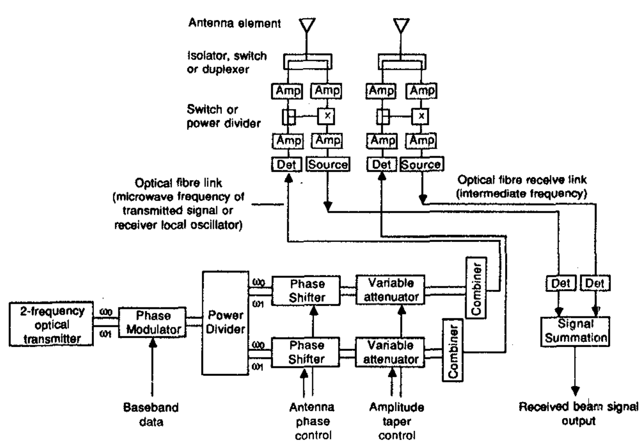

Fig. 3: Coherent optical beam-forming system.

At the array element heterodyne detection takes place in the photodiode to recover the microwave signal, including the phase information. In the transmit mode the microwave signal is amplified and fed directly to the radiating element. In the receive mode the phase controlled difference frequency is used as a local oscillator signal to convert the incoming signal from the antenna element to a convenient intermediate frequency in the 1 - 2 GHz range. The resulting IF signal modulates an optical source and fibre transmission to the receive combiner is used.

ALTERNATIVE DETECTION SCHEMES

In most currently proposed systems the optical signal is coverted into the electrical domain using a high speed photodiode followed by several stages of amplification. At the higher microwave frequencies the realisation of large amounts of phase-stable gain becomes more difficult. There has therefore been sustained interest in the direct control of microwave devices using optical signals [6].

Optical injection locking, in which an intensity modulated optical signal locks a microwave oscillator provides a useful optical/electrical interface technique. However, in the phased array application the phase error when the free-running oscillator frequency differs from that of the locking signal is a serious problem.

At University College London a combined optical injection locking/phase locking system has been used to overcome this problem [7]. Figure 4 shows a network analyser display indicating the phase variation with injection locking frequency for the open loop and closed loop systems. The phase change with frequency is absent for the closed loop system. Note that the injection locking path can be of wide bandwidth so that the phase lock loop need only handle low frequencies, thus simplifying circuit design.

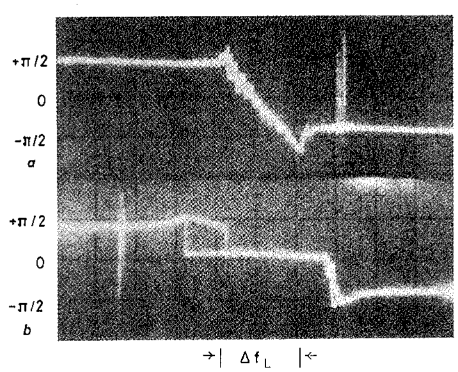

Fig. 4: Optically controlled frequency and phase system. Variation in phase error with frequency: a injection locked oscillator, b combined system. (horiz. freq: 500 kHz/div.; vert. phase: π/2/div.)

CONCLUSION

The attractions of optical signal feeds for phased array antennas are becoming accepted and it is possible to control groups of 10-200 elements from a single laser source. In Europe early application to space-based phased arrays is expected. However, the advantages of reduced mass and improved electromagnetic compatibility are also important in naval applications. Much development work on optical sources and detectors remains to be done to improve the efficiency of the optical/electrical interface.

Optical beam forming is a topic of considerable current research interest and both coherent and non-coherent techniques are likely to find system applications.

In the longer term direct optical control of microwave devices would permit further reductions in array complexity provided the problems of device design to give efficient optical coupling can be overcome.

European groups are contributing to international research efforts in all of these areas and continuing rapid technological development is to be expected.

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