NEW DEVELOPMENTS IN OPTICAL CONTROL TECHNIQUES FOR PHASED ARRAY RADAR

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ABSTRACT

Recent work on optical signal distribution and control techniques for phased array radar is described. Experimental results for millimetre-wave reference signal generation by heterodyning the outputs of two semiconductor lasers are presented. Novel mixers in which the local oscillator input is an intensity modulated optical signal are described. The use of these developments, together with other optically controlled devices, in new phased array element architectures is discussed.

INTRODUCTION

The wideband transmission capability of single mode optical fibre coupled with its light weight and immunity from electromagnetic interference has led to considerable interest in its use for signal distribution in active element phased array radar systems (1,2). This has been supplemented by work on the use of optical techniques for antenna beam formation (3) and on the optical control of microwave oscillators (4-6). The present paper describes recent work in three important areas- optical wideband signal distribution, optical reference signal generation by laser heterodyning and the creation of new, optically controlled, circuit functions- and discusses how these developments may affect phased array element architecture.

WIDEBAND SIGNAL DISTRIBUTION

Figure 1 shows a simple optical fibre feed network for an active element phased array radar. In general microwave reference signals, received signals at intermediate frequency, and control and monitoring signals will all be candidates for transfer through the network. However, attention will be concentrated on the microwave reference signal since it is the highest frequency present, with strict

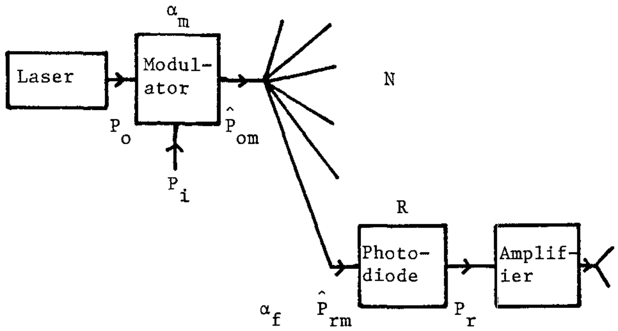


Figure 1: Feed network for optical signal distribution.

requirements on close to carrier noise and phase across the array. In the figure the electrical reference signal drives an external optical modulator, although bias current modulation of the semiconductor laser can also be used. The resultant intensity modulated optical signal passes through the single mode fibre feed network to the photo-detector where the modulation is recovered for subsequent electronic processing in the element. Phase control can be implemented by switched optical delay in the feed network, although losses in presently available integrated optic switches would need to be reduced considerably to make this option attractive.

An important parameter of the feed network is the loss between modulator input and detector output. For an interferometric modulator used in the network of Figure 1 the output power is

$$P_r = \frac{R_{in}}{2 N^2}[\alpha_m \alpha_f R P_o J_1(k_p(2 R_o P_i)^{\frac{1}{2}})]^2 \qquad \text{---(1)}$$

where α_m is the loss factor of the modulator, k_p its phase constant, R_o its input resistance, α_f the excess loss factor of the feed network, N the number of elements fed, R the responsivity of the photo-detector, R_{in} the input resistance of the detector amplifier, P_o the output power of the laser, P_i the modulating power and $J_1(x)$ a first order Bessel function of the first kind with argument x. For small x, corresponding to low values of modulating power the loss can be written

$$\frac{P_r}{P_i} = \frac{R_{in}\, R_o\, [\alpha_m\, \alpha_f\, R\, P_o\, k_p]^2}{4\, N^2} \qquad \text{---(2)}$$

An experimental broadband link (N=1) was constructed using a 1.5 mW output semiconductor laser emitting at a wavelength of 1300 nm as the optical source, with a travelling wave Mach-Zehnder modulator fabricated in lithium niobate (7). The photo-detector was a GaInAs quasi-PIN structure using an indium tin oxide contact which gave a responsivity of 0.4 A/W with a 3 dB bandwidth of greater than 20 GHz. All devices were fibre pigtailed. The system displayed uniform response over the frequency range 1-18 GHz with a loss of 70dB. This value could be reduced considerably by improving the device to fibre coupling and increasing the laser output power.

REFERENCE SIGNAL GENERATION

Bandwidth limitations in monomode fibre feed networks will not usually be significant; for example 1300 nm wavelength single mode fibre offers a bandwidth distance product of over 100 GHz km with a semiconductor laser source (8), while path lengths in feed networks are unlikely to exceed 20 m. Very wideband Schottky photodiodes have also been fabricated (9). However, it is difficult to obtain optical modulation at frequencies in excess of 20 GHz using either external modulators (7) or directly modulated semiconductor lasers operating at room temperature (10).

Goldberg et al (11) have demonstrated an ingenious technique for generating optical reference signals modulated at millimetre-wave frequencies using FM sideband injection locking of an external cavity semiconductor laser. The locking range achieved was about 350 MHz.

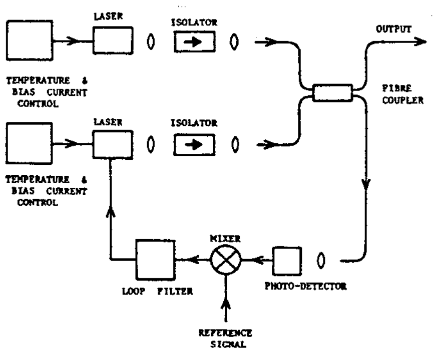
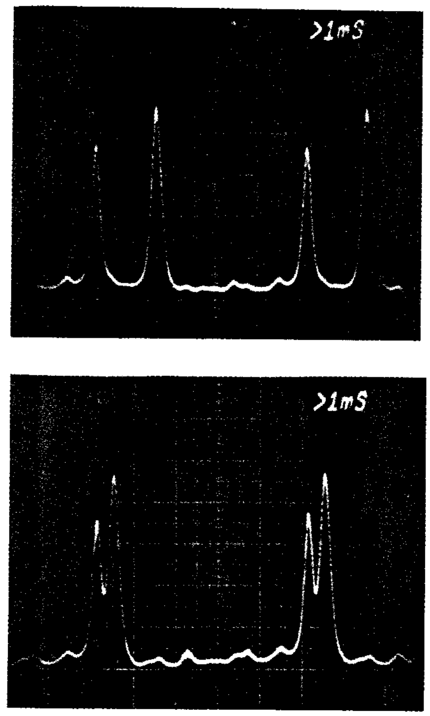


Figure 2: Laser heterodyne system for reference signal generation.

Figure 2 shows a method of obtaining greatly increased frequency agility; laser heterodyning. In this, the optical fields of two single mode semiconductor lasers of slightly offset wavelengths are superimposed in a single mode optical fibre coupler. This signal is then applied to the fibre feed network. At the photo-detector the square law nature of the detection process generates an electrical signal at the difference frequency between the laser outputs: this frequency can be controlled by varying the laser drive current and temperature. By using an additional photo-detector and mixer, with an appropriate loop filter, it is possible to lock the heterodyne frequency to a microwave reference source (12).

Figure 3 shows Fabry-Perot interferometer scans for heterodyne frequencies of 29 GHz (a) and 8 GHz (b), for a system using Hitachi HLP 1400 lasers at a wavelength of about 830 nm.



(a)
29 GHz
heterodyne

(b)
8 GHz
heterodyne

Figure 3: Fabry-Perot scans for optical heterodyne system. FSR: 100 GHz. Vertical scale: optical power (linear).

Figure 4 shows a detected heterodyne at 6.8 GHz (open loop system). The sidebands spaced 270 MHz from the heterodyne frequency are due to residual optical feedback from the cleaved fibre ends being coupled back to the lasers through the optical isolators. Such feedback can be reduced by anti-reflection coating the fibre ends and careful alignment of the optical

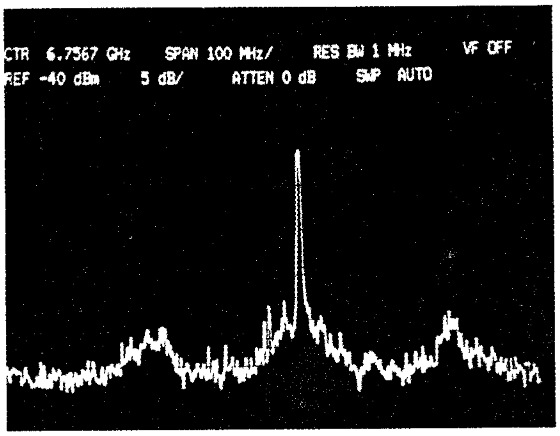


Figure 4: Detected laser heterodyne at frequency 6.8 GHz (open loop system).

components. The measured open loop linewidth of the heterodyne signal was about 10 MHz. However, when the loop is locked the linewidth is reduced to approximately that of the microwave reference signal (12).

The upper frequency limit for the heterodyne technique is set by the photodiode used and can thus be in the high millimetre-wave region (9). Practical difficulties are the sensitivity of the lasers to optical feedback and temperature changes (temperature coefficient ≅ 20 GHz/K for the HLP 1400). The latter problem can be reduced by employing external cavity techniques, at the expense of a more limited heterodyne frequency tuning range.

OPTICALLY PUMPED MIXERS

The feed network considered so far has used direct detection of the reference signal, with subsequent processing in conventional electronics. An alternative approach is to adapt microwave devices to permit direct optical control. Extensive investigations of optically controlled oscillators have already been carried out (4-6). More recently mixers which use an intensity modulated optical source as the local oscillator signal have been developed (13,14). Figure 5 shows the structure of such a mixer using tunnelling in a Schottky-N^+ GaAs contact as the mixing mechanism. Figure 6 shows the modelled and measured conversion loss at an input frequency of 100 MHz, as a function of bias, using a directly modulated low power (3 mW) semiconductor laser as the local oscillator source. The minimum conversion loss obtained was about 20 dB, although modelling studies indicate that this could be reduced to 10 dB with a laser power of 12 mW.

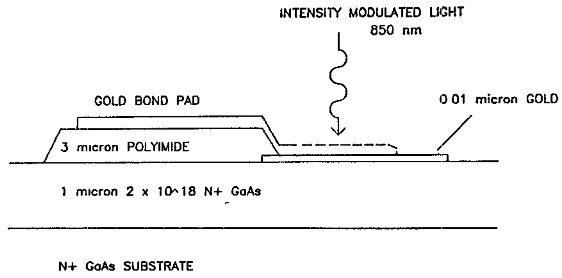


Figure 5: Tunnelling optically pumped mixer structure.

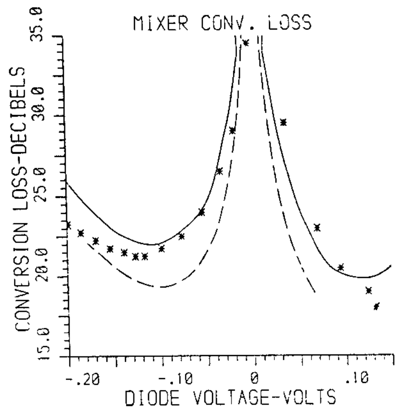


Figure 6: Conversion loss of optically pumped tunnelling mixer. $\lambda = 780$ nm, $P_{op} = 3$ mW, $I_{dc} = 120$ μA, f = 100 MHz.

In phased array radar applications the optical local oscillator power requirement is crucial since the reference signal power has to be divided between the array elements. The narrow depletion region of the tunnelling mixer results in low quantum efficiency and hence a high optical power requirement for large arrays. A Mott structure has recently been proposed (14) which offers predicted conversion losses of 10 dB at X-Band with an optical local oscillator power of 3 mW. Measurements to confirm these predictions are currently in progress.

ARRAY ELEMENT ARCHITECTURE

The development of novel optically controlled devices offers the possibility of new array element architectures. Figure 7 shows a receive array using optically pumped mixers in which phase shift is applied to the optical local oscillator signal. Figure 8 shows a more complex transceive element using an optically controlled oscillator. Optical injection locking provides frequency synchronisation

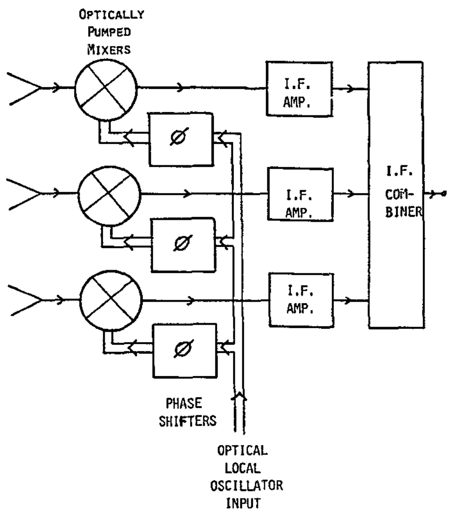


Figure 7: Receive array using optically pumped mixers.

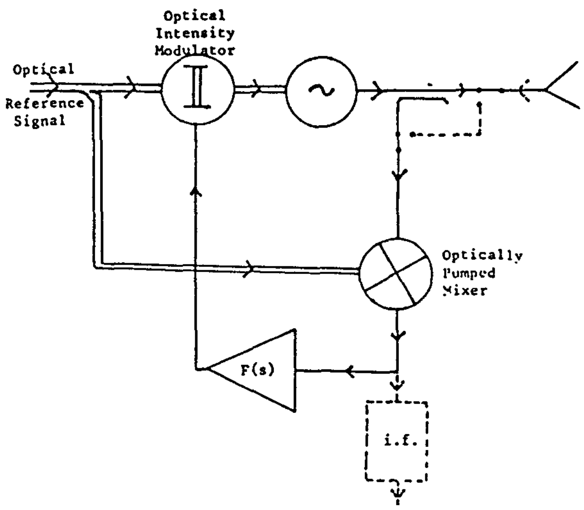


Figure 8: Phased array element using combined frequency and phase control.

for the element (4-6). Phase control is maintained through a phase-lock loop of restricted bandwidth, which controls the average intensity of the locking signal thus producing optical tuning. On receive (dotted path) the optically pumped mixer is used as the first receiver mixer.

CONCLUSIONS

New techniques for reference signal generation and distribution in phased array radar have been described. Laser heterodyning would make reference signal distribution possible in millimetre-wave arrays, where the advantage over conventional feed techniques is especially marked. Optically pumped mixers could find extensive application in phased arrays if the optical driving power can be reduced sufficiently. The provision of sufficient optical reference signal power in large arrays using conventional detection is also likely to pose a significant problem. There is scope for work on the development of laser amplifiers for high rate intensity modulated signals which could be used to feed sub-arrays. Much work is also required on packaging and interconnect technology to minimise optical losses. This area will benefit from the large scale effort for optical communications purposes.

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