# Chirped fibre Bragg gratings for phased-array antennas

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*Indexing terms: Gratings in fibres, Antenna phased arrays*

A variable delay line for phased-array antennas based on a chirped fibre Bragg grating is demonstrated. The time delay of a microwave modulating signal is modified by scanning in wavelength a chirped grating. In this initial experiment, time delay variations up to 556ps have been achieved using a grating of 0.4nm bandwidth and 6cm length and modulating in the frequency range 390MHz–5.20GHz.

*Introduction:* There has been a surge of interest in the use of monomode optical fibres for signal distribution in phased arrays antennas, apart from the reduction in mass and cost of the beamforming network the use of optical distribution networks has a number of advantages such as low insertion loss, high phase stability, immunity to electromagnetic interference and the ability to feed different arrays by WDM [1]. Wideband phased arrays require a true-time delay distribution network in order to keep the beampointing direction at different frequencies stable. Several techniques have been proposed for wideband operation [2] and recently the use of fibre Bragg gratings have been incorporated to fabricate programmable delay lines. A first demonstration of a variable delay line based on fibre gratings was presented by Ball and Morey [3]. A set of gratings of different Bragg wavelengths in an optical fibre were used as a phase shifter for a 17MHz radio- frequency signal. The phase shift of this line is determined by the optical path length between gratings and is controlled by changing the wavelength of the optical carrier. The use of this sort of line as a true-time delay component for phase array antennas has been reported by Molony and Bennion [4]. By using a line with four gratings they demonstrate a linear phase delay of a radio-frequency signal in the range 500–900MHz at three different optical wavelengths. Two of these lines have been integrated in a novel architecture by Tong and Wu [5] to fabricate the first 2 bit beamforming network based on fibre gratings. By commuting different lines of the beamforming network it is possible to steer the beam radiated by the antenna at discrete directions within its maximum coverage angle.

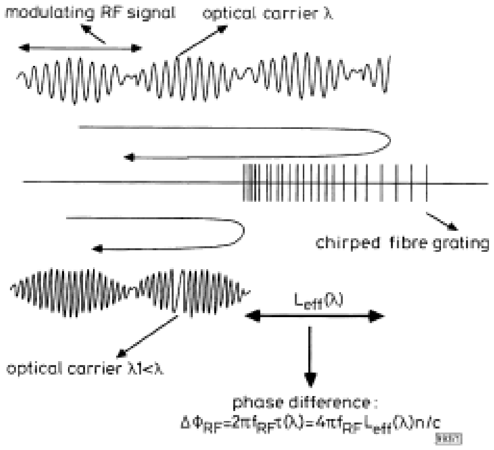

**Fig. 1** *Schematic diagram of fibre grating working as microwave phase shifter*

Two different optical wavelengths λ and λ1 travel different distances in grating, delaying phase of microwave modulating signal

Phase shifters formed by uniform gratings supply a phase distribution to the ports of the array antenna given by the distance between adjacent gratings. Since the length of fibre between gratings cannot be modified in a continuous manner the orientation of the principal lobe radiated by the antenna can only be switched in a discrete set of angles. We propose in this Letter the use of chirped fibre Bragg gratings as a true time-delay line for continuous steering of microwave phased array antennas. In this initial experiment we demonstrate that a chirped grating can produce a linear phase delay of the modulating signal at microwave frequencies and that the slope of the phase response can be continuously modified by tuning the wavelength of the optical carrier.

*Principle:* A chirped grating is a highly dispersive reflector whose time delay '$\tau(\lambda)$' depends strongly on the optical wavelength λ. If an optical carrier is modulated by a microwave signal of frequency $f_{RF}$, the microwave signal suffers a phase delay given by $\Delta\Phi_{RF} = 2\pi f_{RF}\tau(\lambda)$. Hence, the fibre grating produces a linear phase shift in the modulating signal whose slope can be continuously varied by changing the wavelength of the optical carrier. The basic principle of operation of a chirped fibre grating as a microwave phase shifter is graphically illustrated in Fig. 1: assuming that each wavelength is reflected from a single point of the grating, different wavelengths travel different distance $L_{EFF}(\lambda)$ in the grating and the modulating signal suffers a delay dependent on the depth reached by the lightwave in the grating: $\Delta\Phi_{RF}= 4\pi f_{RF}L_{EFF}(\lambda)n/c$, where $n$ is the average refractive index along the grating and the $c$ the velocity of light.

Note that this device behaves as true time-delay line provided that the time delay of the modulated signal is independent of the modulation frequency, thus the modulation frequency must be low enough to preserve the linewidth of the optical light spectrum.

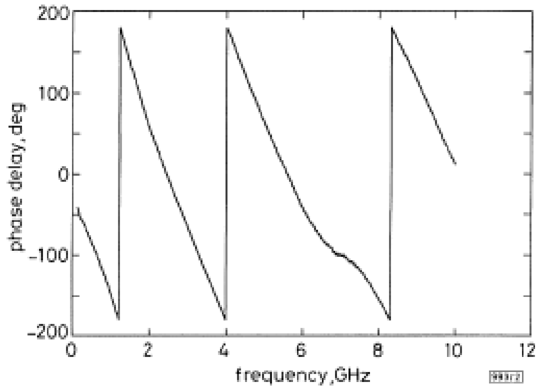

**Fig. 2** *Measured phase delay of microwave signal against frequency*

Wavelength of optical carrier: 1555.25nm

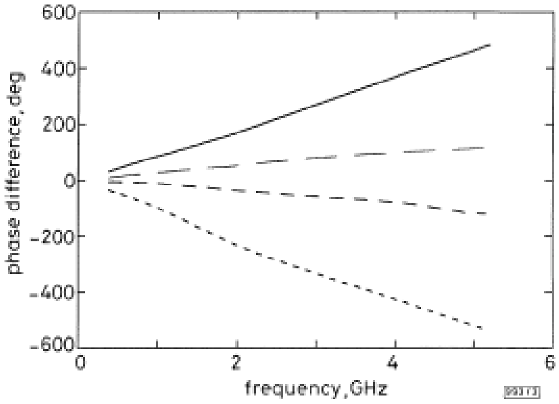

**Fig. 3** *Measured phase delay of modulating signal in L and S microwave bands at different optical carrier wavelengths*

‐ ‐ ‐ ‐ ‐ 1555.25nm
– – – – 1555.36nm
— — 1555.44nm
——— 1555.55nm

*Experiment:* To test the ideas developed above we used a chirped fibre grating with central Bragg wavelength at 1555.4nm and 0.4nm bandwidth. The grating had an effective length of 6 cm and a dispersion of 1400ps/nm. A tunable laser was used as light source. The light was intensity modulated by an electro-optic modulator with a radio-frequency signal supplied by an RF network analyser. The modulated light was launched into the grating via a 3dB coupler. The reflected light was detected by a fast diode and the RF signal studied with the network analyser.

The response of the grating against the modulating RF frequency is shown in Fig. 2. The curve shows that there is a linear dependence on frequency up to ~5GHz, and a nonlinear response at frequencies higher than 5GHz. The nonlinear behaviour at high frequency is due to the broadening of the light spectrum. The laser linewidth modulated at 10GHz is ~0.1nm and becomes comparable to the grating bandwidth. The use of a broader grating will help to increase the maximum operation frequency. Gratings with chirps of several nanometres can be fabricated [6].

Fig. 3 shows the phase response of the grating at different wavelengths. We can see that the time delay of the microwave signal (the slope of the phase curve) can be modified by tuning the wavelength of the optical carrier. The phase difference exhibits a reasonable linearity with frequency for all the tested wavelengths. The maximum time delay difference computed from the two extreme phase curves is 556ps.

The spacing $d$ between the antenna elements must be chosen to avoid grating lobes in the radiation pattern. The spacing criterion in terms of the maximum scan angle $\theta_{MAX}$ is:

$$\frac{d}{\lambda_{RF}} < \frac{1}{1+\sin(|\theta_{max}|)} \qquad (1)$$

where $\lambda_{RF}$ is the microwave wavelength. Since the time delay $\tau$ between extreme elements and the scan angle are stable related by $\tau = (N-1)\{d/c\}\sin\theta$, the maximum angle the array can cover is given in terms of the time delay between extreme elements of the array:

$$\sin(|\theta_{max}|) \leq \frac{\frac{\tau}{N-1} f_{max}}{1-\frac{\tau}{N-1} f_{max}} \qquad (2)$$

where $N$ is the number of elements of the array and $f_{MAX}$ is the maximum operation frequency. Using eqn. 2 and the time delay computed from Fig. 3 we conclude that this particular grating could steer an array of eight elements within an angle of ±42°. Larger arrays will require the use of larger gratings. At present, state of the art gratings of tens of centimetres can be fabricated [7].

*Conclusions:* We have demonstrated that chirped fibre gratings can be used as variable true-time delay lines for phase array antennas. The main advantage of this element lies in its ability to produce continuous steering of the array scan angle by tuning the wavelength of the optical carrier. Time delay differences of 556ps have been measured in the L and S microwave bands.

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