# MICROMACHINED SUB-MILLIMETER & MILLIMETER WAVE VARIABLE POLARISATION COMPENSATOR

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***Abstract* — A micromachined variable polarisation compensator has been designed and demonstrated experimentally at 100GHz. The device uses two interlocking artificial dielectric gratings to produce a birefringence that varies as a function of the separation distance. The maximum phase difference was measured to be 74°, in good agreement with computer simulations. Quarter wave dielectric anti-reflection coatings can be added to the exterior surfaces to reduce the insertion loss.**

## I. INTRODUCTION

Variable polarisation compensators are well known in classical optics [1], where the compensation is varied by altering the path length through a fixed-birefringence crystal such as calcite, or electrically altering the birefringence of a fixed thickness of a crystal such as lithium niobate. No analogues for these behaviours exist at millimeter and sub-millimeter wavelengths. However, sub-wavelength artificial dielectric gratings can be made to exhibit strong birefringence, providing a low-cost, compact alternative to devices such as box prisms in communications and instrumentation applications [2]-[4].

This paper describes the experimental demonstration of a micromachined silicon variable artificial dielectric retarder (VADR) that provides variable polarisation compensation at 100GHz. The theory of operation is explained in section II. The device is wavelength specific, but the fabrication process described in section III easily scales to the dimensions required for operation at millimeter and sub-millimeter wavelengths. The experimental procedure, results and verification by computer simulation are presented in section IV, and discussed in section V. Further simulation results, investigating the addition of quarter-wave dielectric anti-reflection coatings, are presented in section VI.

## II. THEORY OF OPERATION

Artificial dielectrics, in the form of dense arrays of pyramidal structures patterned into a substrate, are widely used for the reduction of reflections at optical surfaces. To a first approximation, incident radiation with a free space wavelength greater than four times the period of the pyramid array experiences a continuous film of smoothly graded effective dielectric constant. It is the smooth grading that reduces the reflection coefficient.

For the fabrication of artificial dielectric waveplates, birefringence is desirable and can be introduced by replacing the two-dimensional pyramid array with a linear V-groove grating. A VADR variable polarisation compensator is constructed from two such plates with identical interlocking sub-wavelength V-grooves in the interior surfaces, as shown in Fig 1.

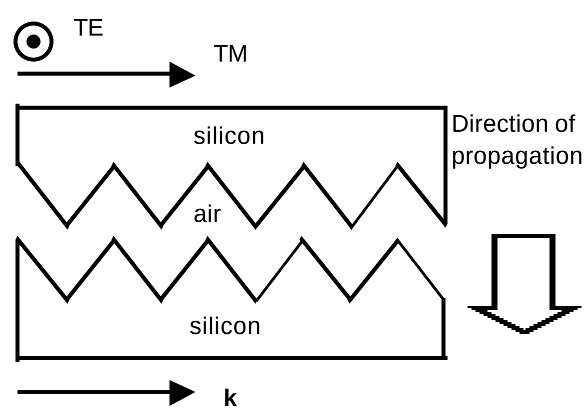


Fig.1 Cross section of VADR device, with plates separated, showing electric field and grating vector directions.

There is no birefringence when the plates are fully interlocked, as the device is effectively a single, uniform dielectric slab. As the plates are separated, the birefringence of the emerging V-groove artificial

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dielectrics increases. Once the plates are fully separated, the device acts as a Fabry-Perot resonant cavity with birefringent mirrors, and the total birefringence oscillates as a function of separation distance [5].

## III. Fabrication

VADR plates have been fabricated with bulk silicon micromachining techniques. A 100mm-diameter (100)-orientation p-doped silicon wafer of resistivity 10-20 -cm was coated in 200nm of silicon nitride and cleaved into 20mm by 22mm samples. The silicon nitride on each sample was reactive ion etched (RIE) in CHF3 / Ar, pressure 25mTorr, power 200W, temperature $275^{o}$K and duration 10 minutes to form a linear grating of period 500μm and line width 40μm. Each plate was wet etched in 40 % w/w potassium hydroxide (KOH) at $80^{o}$C for 280 minutes. The KOH solution etches vertically at 1.2μm/minute, but is prevented from etching laterally by the (111) etch stop planes that extend from mask edges at an angle of $54.7^{o}$ to the surface [6]. These etch stop planes form the sloping sidewalls of the V-grooves, as shown in Fig. 2. Two such gratings are interlocked to form complete VADR devices.

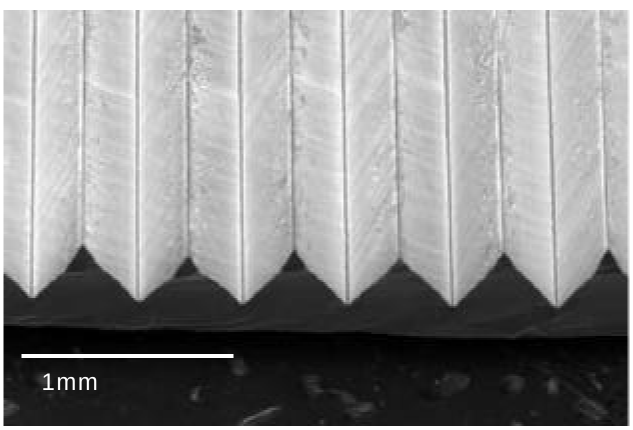


Fig. 2 Scanning Electron Microscope micrograph of a VADR plate.

The long etch times necessitate close control of process parameters. The linear grating must aligned to within $0.5^{o}$ of the (110) traces on the wafer surface to ensure that mask undercut is minimised. Excessive mask undercut exposes the V-groove tips, leading to rapid erosion (1.2μm/minute), and eventual destruction. Prior to wet etching, an oxygen plasma ash removes passivating organic compounds from exposed silicon surfaces and a hydrofluoric acid dip dissolves native silicon oxide formed during the ashing.

## IV. Experimental and Simulation Results

The transmission of a -15dBm 100GHz beam through VADR devices was measured using pyramidal transmitting and receiving horns connected to a W-band vector network analyser, as shown in Fig 3. The VADR device was rotated so the normally incident beam was linearly polarised with electric field perpendicular to **k** (transverse electric (TE)) and parallel to **k** (transverse magnetic, TM), where **k** is the grating vector as shown in Fig 1.

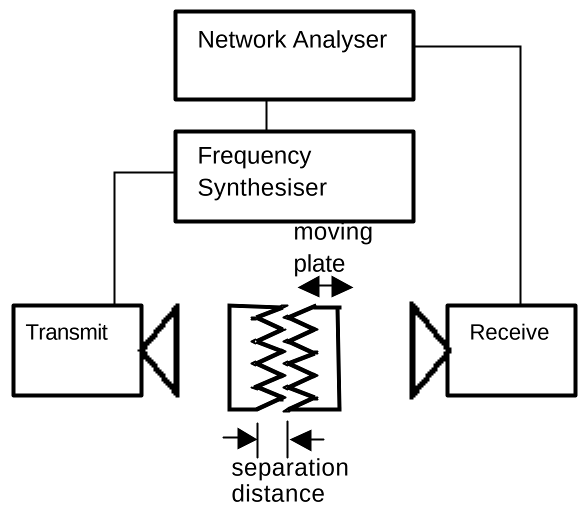


Fig. 3. Experimental set up.

Each plate was mounted over a fibreglass (FR-4) aperture and affixed with double-sided adhesive foam. One holder was mounted on a fixed support, the other on a micrometer-driven translation stage that controlled plate separation. Both holders were covered with absorbing foam to reduce field leakage around the aperture, other metal surfaces were covered to reduce reflections. VADR was first mounted for a TE polarisation and S-parameters were recorded for a range of plate separations (0 - 350μm in 20μm steps, 350μm - 3050μm in 60μm steps). The VADR was rotated $90^{o}$ and the experiment repeated for the TM polarisation. The complex transmission coefficients are plotted as solid lines in Fig. 4, with TE magnitude in 4(a), TM magnitude 4(b), TE phase 4(c) and TM phase 4(d). Note that the phase is raw data, but the magnitude data has the test fixture's insertion loss (8.5dB) removed. The difference in the phase response between TE and TM polarisations is the birefringence property that is desired, and this is plotted as a solid line in Fig. 5.

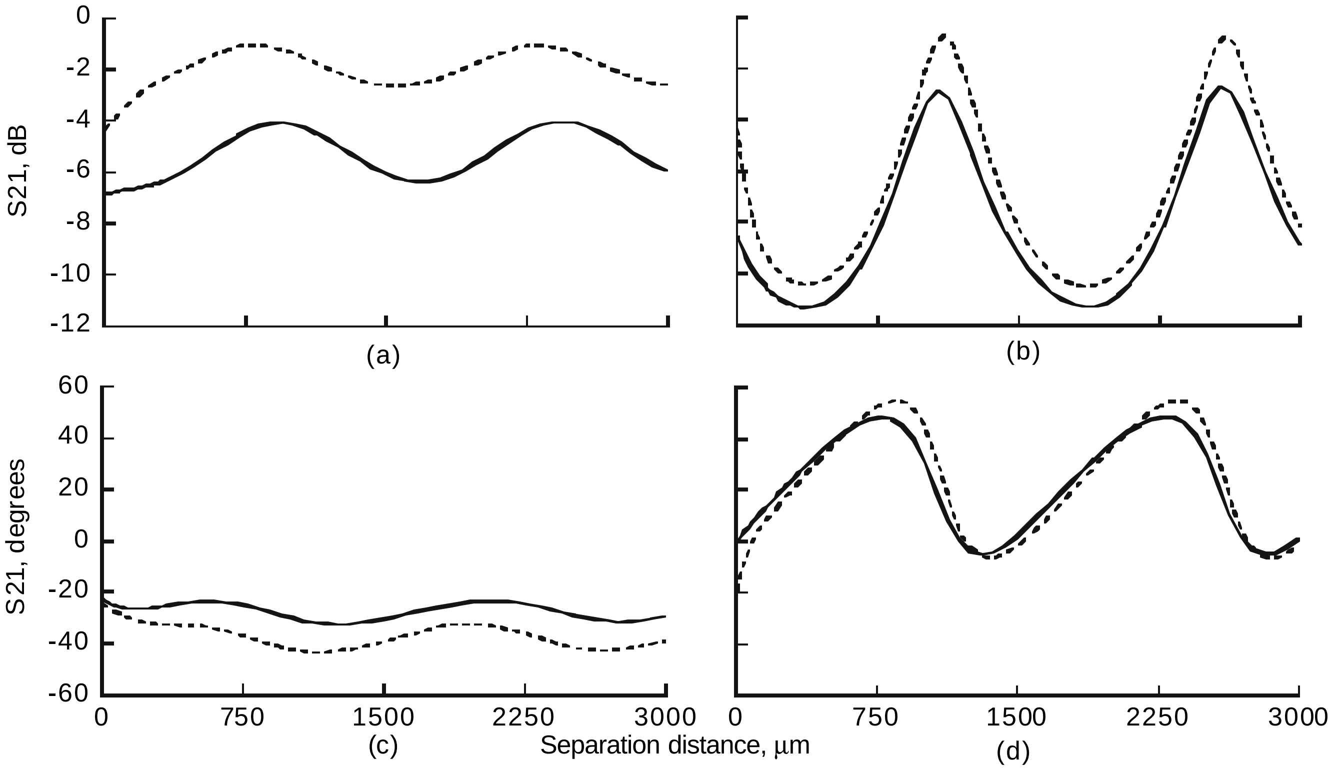


Fig. 4 Complex transmission coefficients of VADR variable polarisation compensator for incident TE and TM linearly polarised radiation, TE magnitude (a), TM magnitude (b), TE phase (c), TM phase (d). - - - simulation ——— measurement

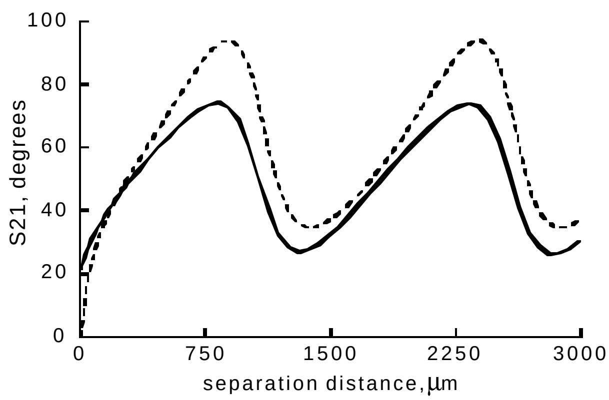


Fig. 5. Phase difference between TE and TM polarisation.
- - - simulation ——— measurement

The expected performance of the VADR devices has been simulated using a commercial rigorous coupled-wave analysis package [7]. The silicon substrate was modelled with complex refractive index n = 3.42 + 0.0384i for 200Ù-cm silicon [8]. A ten-layer staircase structure approximated the V-grooves. The simulations modelled the interlock region (0 - 350µm) in 35µm steps, and the remainder (350 - 3000µm) in 50µm steps. The complex transmission coefficients were extracted, and are plotted as dashed lines in Fig. 4(a)-(d). The phase difference between the TE and TM polarisations is plotted as a dashed line in Fig. 5.

## V. DISCUSSION

The phase difference between the TE and TM polarisation, plotted in Fig. 5, gives a measure of the birefringence of the device as a function of the plate separation. The maximum phase difference of $74^o$ was measured at a separation of 830µm. For complete polarisation control, a full quarter wave shift is required. This could be achieved with two coupled VADRs, each at a separation of 300µm. Such shifts are manageable by piezoelectric actuators. The first area of operation is in the interlock region, where separation distance is less than the groove depth. The phase difference changes linearly, from $22^o$ to $34^o$, for separation distances 0-100µm, yielding a sensitivity of $120^o$/mm. A $0^o$ shift was not observed due to mechanical imperfections inhibiting full interlock. A second region of linear phase shift lies between separations of 1000 - 1300µm, giving a relative phase difference of $36^o$, and sensitivity of $-120^o$/mm. Over the

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entire operating range, the insertion loss oscillates between 4 - 7dB for TE and 3 -11dB for TM radiation (Fig. 4 (a), (b)).

The simulations correctly predict the shape of the oscillation in the phase of the TM response, the relative magnitudes of the oscillations in both phase and magnitude responses, and the positions of the peaks and troughs of those oscillations (see Fig. 4). Quantitatively, the measured and simulated results for the TM polarisation agree within 2dB and $10^{o}$ for magnitude and phase respectively, while the TE polarisation shows discrepancies of up to 4dB and $11^{o}$. The differences between the experimental and simulated data arise from the finite size of the test structure, resulting in field leakage.

## VI. REDUCING THE INSERTION LOSS

The two exterior surfaces of the VADR device form an additional pair of strongly reflecting mirrors, due to the abrupt substrate-air interface. This results in an increase in, and a mismatch between, the TE and TM insertion losses. Simulations with 405µm thick, loss-less, quarter-wave dielectric anti-reflection coatings (n = 1.85) on the two exterior surfaces predict an improved, equal insertion loss of 0.5 - 3.5dB for both TE and TM polarisations, as plotted in Fig 6.

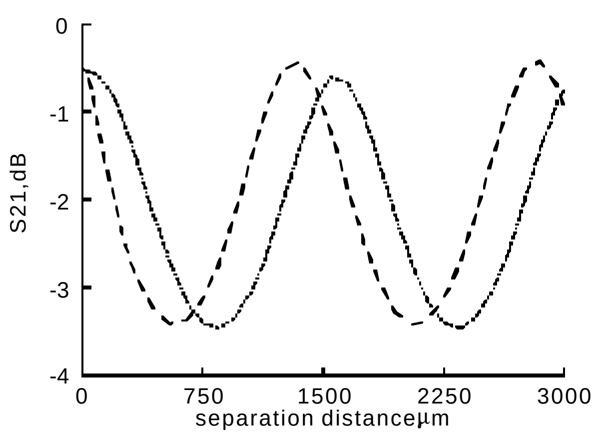


Fig. 6 Insertion loss for TE and TM polarisations with anti-reflection coating. ······· TE ▬ ▬ TM

The peak phase difference reduces to $63^{o}$, and the oscillation to $20^{o}$. The performance of the anti-reflection coated model closely matches that of the two-mirror multiple multi-pole (MMP) model presented in the device proposal [5].

## VII. CONCLUSION

A variable polarisation compensator using artificial dielectrics has been fabricated, tested and modelled at a frequency of 100GHz. Phase shifts of up to $74^{o}$ have been measured, in good agreement with simulations. The phase shift can be greatly modified for small, easily controlled, changes in separation distance. Operation is wavelength specific, but the fabrication process scales easily. The addition of anti-reflection coatings to the two exterior surfaces reduces the insertion loss. The VADR devices provide a compact, low-cost alternative to classical optical compensators at sub-millimeter and millimeter wavelengths.

## AKNOWLEDGEMENTS

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