A K-Band Linear Phased Array Antenna Based On Ba$_{0.60}$Sr$_{0.40}$TiO$_3$ Thin Film Phase Shifters

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A K-BAND LINEAR PHASED ARRAY ANTENNA BASED ON 
$\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$ THIN FILM PHASE SHIFTERS

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ABSTRACT
This paper summarizes the development of a 23.5 GHz linear 16-element scanning phased array antenna based on thin ferroelectric film coupled microstripline phase shifters and microstrip patch radiators.

INTRODUCTION
A prototype scanning 16-element linear phased array using $\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$ films on 0.3 mm thick MgO has been developed. The array is intended to be a steppingstone to collision avoidance radar suitable for automotive applications because of its potential to provide a much lower cost solution for certain Intelligent Vehicle Highway Systems. The phase shifters are based on a series of coupled microstriplines of length $l$ and separation $s$ patterned over pulsed laser deposited $\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$ films nominally 400 nm thick. The maximum coupled voltage occurs when the coupled sections are a quarter wavelength long (i.e., $\beta l = 90^\circ$). Bias up to 400 V is applied to the sections via printed bias-tees consisting of a quarter-wave radial stub in series with a very high impedance quarter-wave microstrip. By concentrating the fields in the odd mode, the phase shift per unit length is maximized and by using the ferroelectric thin film form the effects of high loss tangent are minimized. Selecting the strip spacing $s$ involves a compromise among: minimizing insertion loss, simplifying lithography, and minimizing the tuning voltage. Strip widths are chosen to approximate a 50 $\Omega$ characteristic impedance. These coupled microstrip devices rival the performance of their semiconductor counterparts at Ku- and K-band frequencies. Typical insertion loss for room temperature ferroelectric 360° phase shifters at K-band is $\approx 5$ dB [1-3].

PHASE SHIFTERS
The multilayer phase shifters have been analyzed using a computationally efficient variational method to calculate the even and odd mode capacitance [4,5]. If a quasi-TEM type of propagation is assumed the propagation constant an impedance can be completely determined from line capacitance. Since the cascaded coupled line circuit resembles a series of one-pole bandpass filters, as the dc bias increases, the dielectric constant of the BST film decreases, causing the passband to rise in frequency (and the $\tan \delta$ of the BST to decrease). The impedance matrix of the cascaded network can be derived by well-known coupled line theory using the superposition of even and odd mode excitation. Then an equivalent S-parameter model can be extracted and used to predict the pass-band characteristics of the phase shifter.

The bandwidth compression from tuning is evident in fig. 1 which is data from an 8-section
phase shifter on 0.3 mm MgO using a 400 nm 
Ba_{0.60}Sr_{0.40}TiO_3 laser ablated film. The roll-off at 
the upper end of the frequency range is attributed to 
bias-tee effects. The bias tees have a 25 µm wide, 
1.83 mm long high impedance line connected to a 
radial stub with flare angle of 75° and radius 1.17 mm.

**PHASE ARRAY DESIGN**

The 23.5 GHz array consists of a monolithic 1:16 
microstrip beam forming manifold constructed on 
0.25 mm thick Duroid 6010, 16 ferroelectric phase 
shifters patterned on ≈1×0.75 cm MgO substrates, and 
a monolithic set of microstrip patch radiators patterned 
on 0.25 mm thick Duroid 5880. Inter-element spac-
ing is 7.49 mm, which corresponds to about 0.57 free-
space wavelengths. The layout is shown in fig. 2.

The original manifold, which had each successive branch of the divider networks separated by only 
1.3 mm, experienced severe coupling problems resulting in considerable loss and asymmetry between 
ports. The distance was increased to 4 mm and resulted in a uniform insertion loss of about 13.0 ±0.25 
dB. The patch array was originally fabricated on high 
dielectric constant material (ε_r = 10.2). However, when 
the resonant frequency of each patch was measured 
using a HP 8510C automatic network analyzer a large 
discrepancy was seen between each one. The varia-
tion was attributed to dielectric constant tolerances. Indeed substrate tolerances are known to cause seri-
sous errors in phased array performance [6]. To circum-
vent the problem a low dielectric constant homog-
enous material was selected. When the array was 
redesigned on 0.25 mm thick Duroid 5880, the varia-
tion in resonant frequency was much smaller, about 
5 percent, and the bandwidth was adequate. Fig-
ure 3 depicts the measured frequency response. The patch dimensions are: L = 4.27 mm, W = 6.40 mm, 
and δ = 1.04 mm. The gap between the feed inset and 
patch was 0.38 mm. No particular attention was given to reducing sidelobe levels or reducing spurious 
radiation from the manifold or feed. The measured 
far-field radiation pattern at boresight is shown in 
fig. 4. The E-plane corresponds to the elevation 
direction and the H-plane corresponds to the azimuth 
direction. The array can scan past 45° before the 
appearance of a grating lobe.

An electronic module was designed and built to control the array. It consists of 16 independently addressable dc-to-dc converter channels. A model 
AOB 16/16 analog to digital converter interfaces the controller with a PC. Since the A/D could only source 
5 mA per channel, an operational amplifier buffer 
(OPA547) was inserted between the A/D outputs and Pico Electronics model 12AV500 encapsulated 
dc-dc converters. A 1 W, 1 MΩ resistor is strapped 
across the transformers output to prevent a no-load condition. Since the dc input resistance of the phase 
shifters is >>1 MΩ, the applied voltage is essentially the programmed voltage. A 0.1 µF capacitor rated at 
1 KV provides some filtering. Finally, an LED status 
indicator on each channel senses whether a thermal 
overload condition is present. The controller board is 
shown in fig. 5. It consumes about 25 mA per chan-
nel under normal conditions.

**CONCLUSIONS**

A linear K-band phased array has been demon-
strated using novel coupled microstrip thin film 
ferroelectric phase shifters. The phase shifters capi-
talize on odd mode propagation to maximize phase 
tuning and minimize insertion loss. Despite a fairly 
common misconception that ferroelectric materials 
have too high a loss tangent for practical microwave 
applications, these devices can outperform their semi-
conductor counterparts by several dB. The phased 
array realized with these phase shifter holds prom-
ise to significantly reduce manufacturing costs of 
phase arrays because the phase shifter are litho-
graphed using a simple two-step process. And the 
finest feature size is the strip spacing, about 10 µm, 
compared to perhaps a 0.5 µm gate for a MESFET 
phase shifter at the same frequency. To the best of 
our knowledge, this is the first demonstration of a 
K-band phased array based on ferroelectric films.

**REFERENCES**

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Film BaSrTiO Ku-Band Coupled Microstrip 
Phase Shifters: Effects of Film Thickness, Dop-
ing, Annealing, and Substrate Choice,” IEEE MTT 

Figure 1.—Measured Insertion Loss (including SMA launchers) of an 8-element \( \approx 50 \, \Omega \) PLD coupled microstripline phase shifter at 290 K as a function of bias voltage. Substrate is 0.3 mm MgO with 400 nm Ba\(_{0.60}\)Sr\(_{0.40}\)TiO\(_3\) film. \( l = 350 \, \mu\text{m}, s = 7.5 \, \mu\text{m} \) and \( w = 30 \, \mu\text{m} \). Bandwidth compression from the filtering effect is evident. Marker 1, 2, 3, and 4 are at -5.75, -5.38, -6.00, and -6.49 dB, respectively.

Figure 2.—Layout of the 16 element 23.675 GHz array. The array is 11.9 cm long.
Figure 3.—Measured resonant frequency of patch radiators on 0.25 mm Duroid 5880 (εr = 2.2), 1 oz. Cu clad material.

Figure 4.—Measured far-field E-Plane (elevation) and H-Plane (azimuth) pattern of the 16-element ferroelectric phased array at 23.675 GHz, 0 and 120 degree incremental phase shift.

Figure 5.—Measured far-field H-Plane pattern corresponding to a 120 deg incremental phase shift.

Figure 6.—High voltage controller board for the 16-element phased array. The board measures 19 cm × 14.5 cm. The board accepts a 0–10 V signal from a 16 channel A/D converter and outputs a linear 0–400 V control signal.
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