A DISTRIBUTED FERROELECTRIC SUPERCONDUCTING TRANSMISSION-LINE PHASE SHIFTER

Farhat Abbas† L E Davis† and J C Gallop‡

† Dept. of EEE, UMIST, Manchester M60 1QD UK
‡ NPL, Teddington Middlesex TW11 OLW UK

ABSTRACT

A numerical solution is obtained for a sinusoidal wave propagating along a multilayered structure of superconductors, ferroelectric and dielectrics. An example of a distributed coupled strip-transmission-line phase shifter has been investigated, and such phase shifters may find applications in low-loss tunable microwave components for satellite and ground-based communications.

INTRODUCTION

The high quality factor (Q) of superconductor-based structures have attractions for commercial, military and space-based systems, and the quality and processing of high temperature superconductor (HTS) thin films have been improved thereby permitting the inclusion of HTS-based circuits in working systems. Within these systems there is a requirement for phase shifters and tunable filters.

Recently, the developments of the dielectric properties of ferroelectric thin films, such as $SrTiO_3$ (STO) and $Ba_xSr_{1-x}TiO_3$ (BST), have resulted in efforts to improve ferroelectric/HTS tunable microwave components [1]. Also, it is necessary to minimise ferroelectric losses, while maximising the phase shift, and to minimise the potential problems due to incompatibility between the ferroelectric superconducting materials.

A distributed coupled strip-transmission-line phase shifter is shown in Fig. 1. Broadside-coupled line, Fig. 1, is particularly attractive because the small spacing between lines means that a relative small applied dc voltage can produce the bias field needed for full control of the variable dielectric, and it permits simplified construction, reduced size and greater power-handling capability [2]. The nonlinearity of ferroelectric materials with superconducting surfaces provides an attractive alternative to traditional solid-state and ferrite phase shifters for applications in electronically scanned array antennas and other tunable microwave devices where cryogenic operation is required. Ferroelectric materials offer a variation in dielectric constant with applied dc electric field and temperature that changes the velocity of propagation and hence the relative phase shift through a microwave structure.

THE STRUCTURE AND ANALYSIS

Figure 1 shows the geometry of the coupled parallel-plate transmission lines. The structure consists of two pairs of superconductors, one pair consists of thin films separated by

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the central dielectric 2, the other pair consists of thick films separated by dielectric 1 from the thin films. The thicknesses of the thin films, thick films, dielectrics 1 and dielectric 2 are l_1, l_2, d_1 and d_2 respectively. The wave propagates in the z-direction.

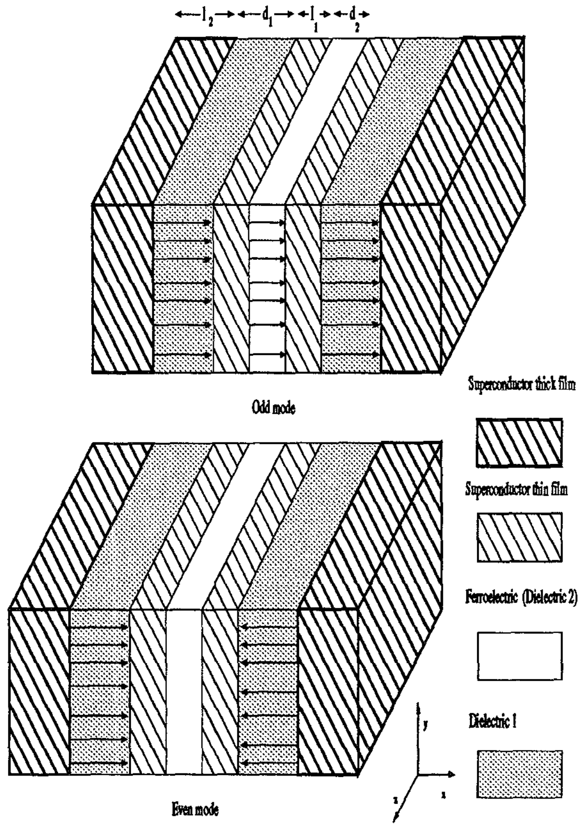

Figure 1: Configuration of tunable microwave multilayers structure considered.

The two-fluid model is used for the superconductors, in which the total current is the sum of the supercurrent and the normal current. Classical skin effect and London theory are assumed for the normal current and the supercurrent respectively. With some simplifying assumptions, it can be shown [3] that the complex propagation constant (α) in the z-direction is given by

$$\alpha^2 = \frac{A \pm \sqrt{A^2 - 4B}}{2} \qquad (1)$$

here $A \triangleq \omega^2\mu_o\epsilon_o\left[\epsilon_1 C + \epsilon_2(1 + \frac{2S_1}{d_2})\right]$,

$B \triangleq (\omega^2\mu_o\epsilon_o)^2\epsilon_1\epsilon_2\left[C + \frac{2S_1}{d_2}(1 + \frac{S_2}{d_1}) + \frac{2\lambda_1^2}{d_2}(\frac{1}{d_1} + \omega^2\mu_o\epsilon_o\epsilon_1 S_2)\right]$,

$C \triangleq 1 + \frac{S_1+S_2}{d_1} + \omega^2\mu_o\epsilon_o\epsilon_1 S_1 S_2$,

$S_1 \triangleq \lambda_1 \coth(\frac{l_1}{\lambda_1})$, $S_2 \triangleq \lambda_2 \coth(\frac{l_2}{\lambda_2})$, and the other symbols have their usual meanings.

The dispersion relation obtained in equation 1 is for two dominant modes of the coupled line. Equation 1 with the positive (+) sign corresponds to the "sum" mode, while with the negative (−) sign it represents the "difference" mode. The sum and difference modes are sometimes referred to as the even and odd or primary and secondary modes, respectively. Further discussion of such modes can be found in [3, 4]. From Figure 1 and equation 1, it can be shown that for the limiting cases where either d_1 or d_2 approach infinity, the structure becomes an uncoupled line and the results are exactly the same as in reference 5.

DISCUSSIONS AND RESULTS

Tunable microwave components based on dielectric nonlinearity using the microwave structure shown in Fig. 1 can be described by the penetration depth λ_r and the normal conductivity σ_r of the superconductors, the dielectric constant ϵ_r of the dielectric, and the thicknesses d and l_r of the dielectric and the superconductors.

The Gorter and Casimir model was used to characterise the superconductors, and the nonlinearity of the dielectric constant ϵ_2 due to the variations of the temperature T (K) and the dc bias electric field E (KV/cm) can be approximated [6] for STO using

$$\epsilon_2 = \frac{M}{(T_1/2)\coth(T_1/T) - T_o} \qquad (2)$$

and

$$\epsilon_2 = -429E^2 + 1.3 \times 10^4 \qquad (3)$$

where $M = 9 \times 10^4 K$, $T_o = 38K$ and $T_1 = 84K$. Equation (3) is obtained by using the MATLAB polyfit routine which fits the data, in a least-squares sense.
Also, equation (1) gives the expression for the differential phase shift

$$\Delta\phi = L\Big[\alpha(E=0) - \alpha(E)\Big] \qquad (4)$$

where L is the length of the line.
Different experimental combinations for a layered microwave structure have been reported in the literature [2], and the derived expressions can be used for any combination of superconductors and dielectric for describing the tunability. Figure 1 shows the operation of the phase shifter considered in this paper. When the even mode is impressed on the structure there is little or no electric field in the ferroelectric material (depending on the thickness of the thin HTS films). Thus, variations in dielectric constant of the ferroelectric will have little or no effect on the phase velocity of the even mode. With the odd mode, a large electric field exists in the ferroelectric region and variations in dielectric constant of the ferroelectric will have a significant effect on the phase velocity.
Let us consider an example in which superconductors 1 and 2 are taken to be thin and thick films of YBCO, and dielectric 1 and 2 are taken to be MgO and STO respectively. The parameters for these materials are taken from the reference 5. The values for the penetration depths for high quality thin and thick films of YBCO are taken to be 140 nm and 2 μm, respectively. The normal conductivity for both thin and thick films is taken to be same and is assumed to be 1.7×10^6 $(\Omega\text{m})^{-1}$.

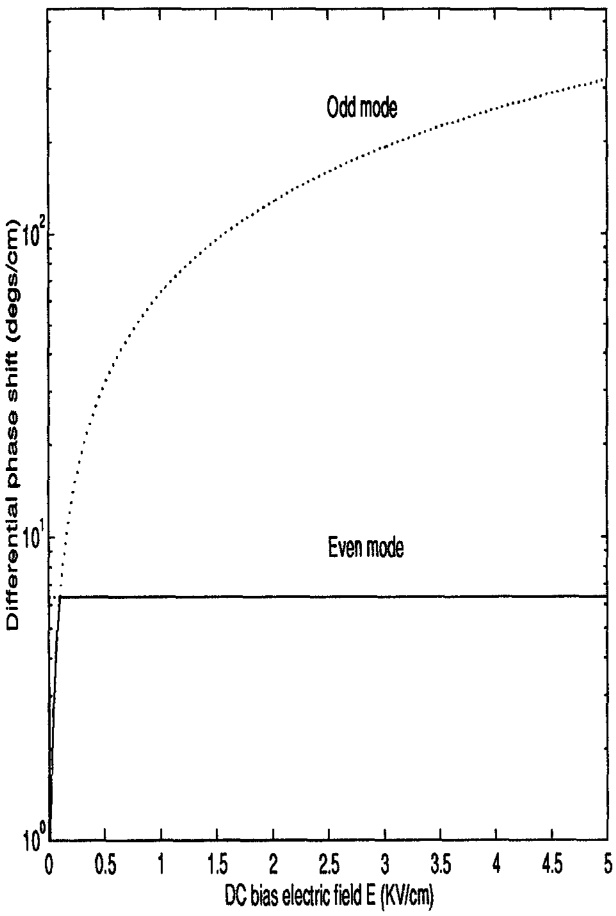

Figure 2: Phase shift per cm versus dc bias electric field E (KV/cm) for even (solid line) and odd (dotted line) modes at $T/T_c = 0.3$ by using two-fluid model of Gorter and Casimir. Other parameters are given in the text.

Using equations (3) and (4) the behaviour of a wave when there are no losses (losses have been considered elsewhere [3] and an estimate is given in the conclusions) in the microwave structure is shown in Figure 2 as a function of the dc bias electric field E (KV/cm). It

is assumed that the two dielectrics 1 (MgO) and ferroelectric (STO) have the thickness $d_1 = 0.3$ mm and $d_2 = 250$ nm, relative permittivities $\epsilon_1 = 9.1$ and $\epsilon_2 = 1.3 \times 10^4$ (unless otherwise mentioned) with the loss tangent $tan\delta_1 = 0$ and $tan\delta_2 = 0$. The operating temperature and frequency are $T/T_c = 0.3$ and 10 GHz, respectively. The thick films of YBCO (superconductors 2) have thicknesses $l_2 = 50\mu$m, i.e approximately 25 penetration depths. The thin films of YBCO (superconductors 1) have thicknesses $l_1 = 300$nm, i.e approximately 2.5 penetration depths.
Fig. 2 shows that the odd mode exhibits strong variation of differential phase shift with increasing dc bias electric field E (KV/cm), e.g. approx. 100 degs/cm with E = 1.5 KV/cm, whereas the even mode is almost independent of E and shows only 6.3 degs/cm with the same bias field. With low values of bias field, e.g. $E \approx 0.1$ KV/cm, the differential phase shift exhibited by both modes is approximately the same, and (although not clearly visible on this scale) both modes exhibit zero differential phase shift when E = 0, as expected. The attenuation of the odd mode is estimated to be of the order of $10^{-2} - 10^{-3}$ dB/cm at 10 GHz.

CONCLUSIONS

A numerical solution is obtained for a sinusoidal wave propagating along a multilayered structure of ferroelectric and superconducting films deposited on dielectric substrates for use in low-loss tunable microwave components for satellite and ground-based communications.
The displacement vector, the dipole moment, polarization, polarizability, susceptibility and relative permittivity concepts are used for ferroelectrics; and for superconductors Bose statistics and the Gorter and the Casimir model for a two-fluid model, London's equations, and the classical skin effect for the normal component of the current are used. A sinusoidal wave solution is found for a planar superconducting transmission line. This solution gives expressions for the phase velocity and attenuation coefficient which are used to characterize the tunability of microwave components. The measured materials data in the literature have been used to compute the relative phase velocities and phase shift per cm versus temperature and the dc bias electric field E (KV/cm). It is shown that with a ferroelectric film of thickness of 140 nm, with $\epsilon_2 = 1.3 \times 10^4$ and $\tan\delta = 10^{-3}$ phase shifts and attenuation of the order of tens of degrees per cm and $10^{-2} - 10^{-3}$ dB/cm, respectively at 10 GHz can be obtained with tens of millivolts at 27 K.

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