DEVELOPMENT OF AN L-BAND FERROELECTRIC PHASE SHIFTER[*]

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Abstract

Effective operation of the RF cavities in superconducting accelerators demands fast, high-power RF vector modulators. Recent progress in the properties of the new composite ferroelectrics - material with tunable dielectric constant and acceptable losses [1,2] - makes the development of such devices possible. In previous papers [3-6] the authors described various L-band ferroelectric phase shifter designs. High switching speed of 2 degree/ns of the waveguide phase-shifter has been demonstrated with the bench test. At the same time these experiments showed that special technology has to be developed to provide the required electric contact between the ceramics and the metallic walls. In the present paper a new design of the fast high–power ferroelectric phase shifter based on ferroelectric ring elements is described.

NEW CONCEPT

The properties of large-sizes ferroelectric bulk elements were investigated in several previous works [3-7]. A 1.3GHz waveguide phase shifter prototype was built and examined [3,4]. This prototype utilized four 5mm×6mm×108mm ferroelectric bars with the permittivity of 500 and four 47mm×6 mm×11.2 mm 'linear' ceramic insertions with the permittivity of 20. The principle of operation was proven and speed of phase control was measured. However, some serious issues were discovered. It was found that it is difficult to provide a good contact between the ferroelectric surface and the metal in this complicated configuration. Poor contacts cause extra losses and degradation in the bias voltage breakdown strength.

Principle of operation

After the aforementioned difficulties intrinsic to configurations utilizing long ferroelectric bars had been identified it was decided that a new more simple geometry was required. A configuration of "resonator in transmission line" was chosen, see Fig.1. Fig.2 explains the principles of operation. The analogy with "transmission resonator in line" is not entirely full because not all the RF energy propagates through ferroelectric volume. Nevertheless we can expect similar behaviour.

Ring shape ferroelectric resonator

The most obvious choice of the shape is a pillbox, Fig.3. The operation mode is TM_{020}. This mode has the largest coupling with a transmission line (waveguide). But the pillbox has a few parasitic modes whose frequencies are close to that of the operation mode. The hole in the centre can detune parasitic modes away from the operation mode. Fig.4. shows one possible geometry of a ferroelectric resonator with brazed metal contacts and how this resonator can be installed in a waveguide.
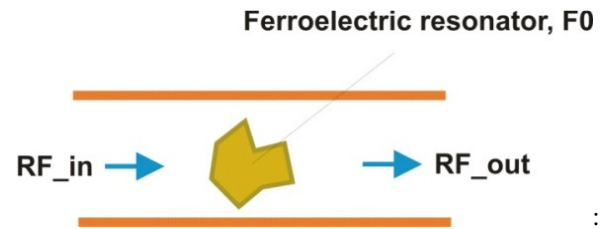

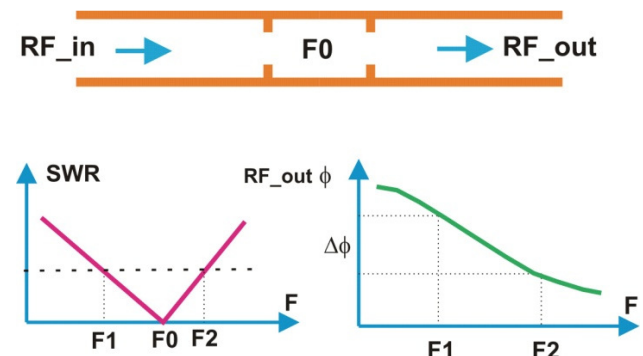Figure 1: Resonator in transmission line.

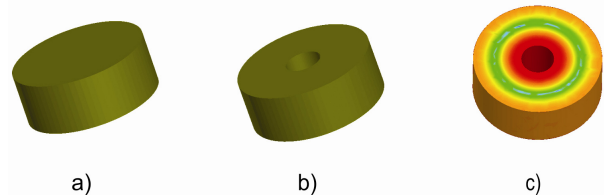Figure 2: Transition resonator, principle of operation.

Figure 3: Most obvious shape of ferroelectric and electric field of operating mode: a) tablet shape, b) centre hole to detune parasitic modes, c) electric field strength of TM_{020} operating mode.
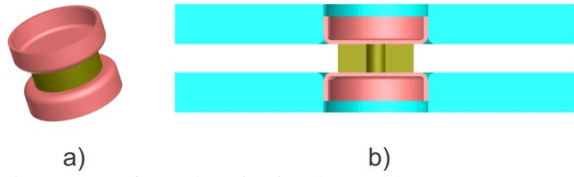
Figure 4: a) ferroelectric ring brazed between two metal cups, b) resonator is installed in waveguide.

Because of the recent progress in developing ferroelectric materials [2], new ferroelectric ceramics have emerged with low permittivity of 300 or even lower [2] as compared to former ceramics with permittivity 500, while still having tunability and losses at acceptable levels. For this design the ceramic with permittivity of 300 has been used. Simulations show that the optimal dimensions of the tablet, which provide maximum frequency gap between the operating and parasitic modes, are: the radius of centre hole R1 = 2.5mm, external radius R2 = 9.53mm, and height H = 10mm. Fig. 5 shows results of simulations of a single resonator installed inside a waveguide. To increase the passband and tunability level, several resonators instead of a single one can be used.
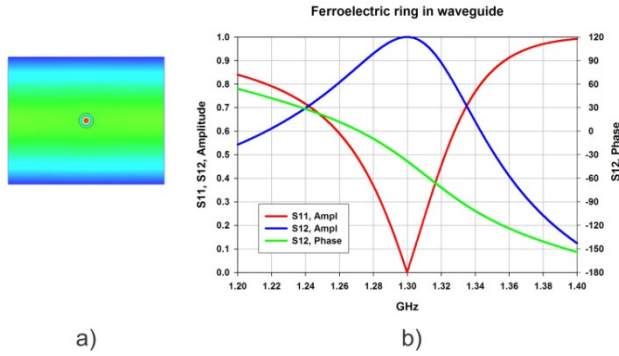

Figure 5: Simulation results for a single ferroelectric ring installed in a waveguide. a) Electric field strength, and b) amplitude and phase frequency characteristics.

Coaxial phase shifter

Coaxial geometry, as we show later, allows one to easily cascade and increase power of the device. Fig.6 shows coaxial geometry with four ferroelectric elements (Fig.9) and electric and magnetic fields strengths. Fig.7 demonstrate amplitude and phase characteristics for three values of permittivity 280, 290 and 300.
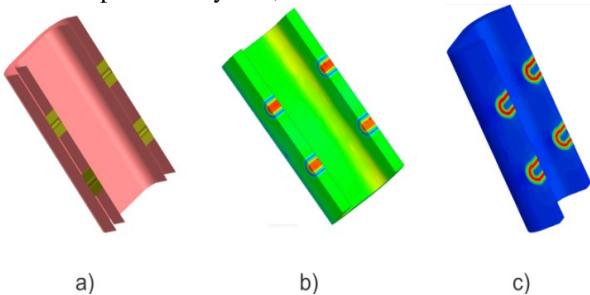

Figure 6: Coaxial geometry with (a) four ferroelectric resonators (Fig.9); (b) electric field strength; (c) magnetic field strength

It can be shown that power losses of this type ferroelectric phase shifter can be approximated by the following formula:

$$\frac{P_{loss}}{P_0} \approx 4tg\delta\frac{\phi_0\varepsilon}{\Delta\varepsilon}, \qquad (1)$$

where P_{loss} is the power loss in ferroelectric, P_0 -incident power, $tan\delta$- loss tangent of ceramic, φ- phase shift, ε - permittivity of ferroelectric, $\Delta\varepsilon$ – required change in permittivity. One observes that the losses for a fixed phase shift are determined by the material properties – loss tangent and tunability $\Delta\varepsilon/\varepsilon$ at a given bias voltage (which in turn, is limited in our case by electric strength requirements). Note that requirements to have minimum losses and high tunability are typically contradictive for a given type of material. Thus, the ratio of the loss tangent to the tunability is the figure of merit for a ferroelectric material in this particular application, but must be considered in conjunction with the fact that $f/tg\delta$ is always almost constant for a given material when the operating frequency changes [1].
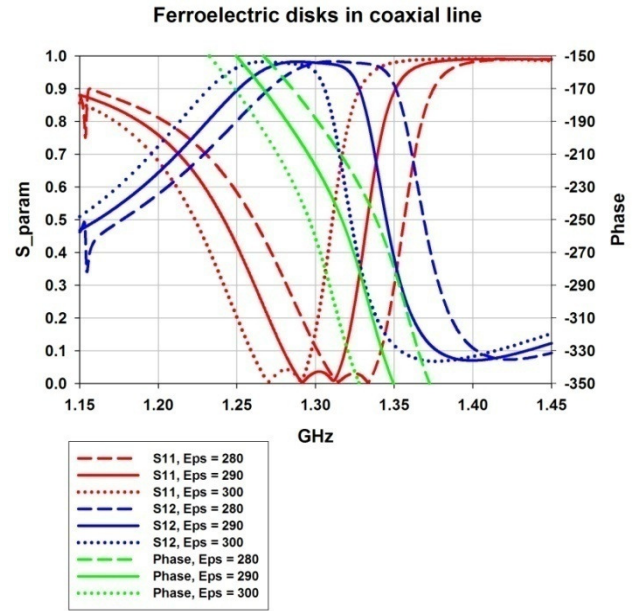

Figure 7: Amplitude and phase characteristics of coaxial geometries for three different values of permittivity 280, 290, 300.

Numerical simulations give more accurate values of losses. Fig.8 shows the calculated loss when the ceramic loss-tangent is 0.001; note that the losses in metal walls are taken into account. One can see (dashed line) that for the phase shift of 50 deg, the losses are about 3%, while an estimation according to (Eq.1) gives 5%. If the transmission line is shortened, the phase of the reflected wave will change by 100 deg, and losses will be 6%. Current properties of ferroelectric ceramic allow changes

in the permittivity from 300 to 280 with the applied external bias of ~15 kV/cm.

Fig. 9 shows a possible geometry of a shorted coaxial phase shifter. High voltage (HV) bias input is not shown. HV can be easily installed in the upper part of the shifter where a pure standing wave exists. The input should be installed in place with zero electric field on the surface. Fig.10 demonstrates a way to cascade several coaxial phase shifters in a waveguide to increase the maximum pulse or average power.

Estimation of the operating power.

The main power limitation comes from heating the ferroelectric material. The temperature rise decreases the dielectric constant of the material as ~2/°C. In the case of CW operations, pre-heating the ferroelectric and temperature stabilization can together increase the CW power limit. Simulations show that losses of 1W in a ferroelectric ring R2=10mm, R1 =2.5mm, H=10mm result in a temperature rise ~ 1°C. If one assumes that the temperature rise 20°C is acceptable (with pre-heating and thermo-stabilization), the acceptable total power loss in four ferroelectric coaxial phase shifter is ~80W or ~6% of the total incident power. Consequently, one 1.3GHz coaxial phase shifter can operate at approximately 1.3kW CW. In the case of operating at 700MHz, the power level will be four times higher because loss in ceramic usually is proportional to the frequency and one can expect losses of about 3%. Additionally, the operating power level can be increased by decreasing the dimension H of the ceramic (thus, decreasing temperature rise). In the case of H=5 mm for 700MHz   a CW power limit of a single coaxial phase shifter can be estimated as ~20kW.
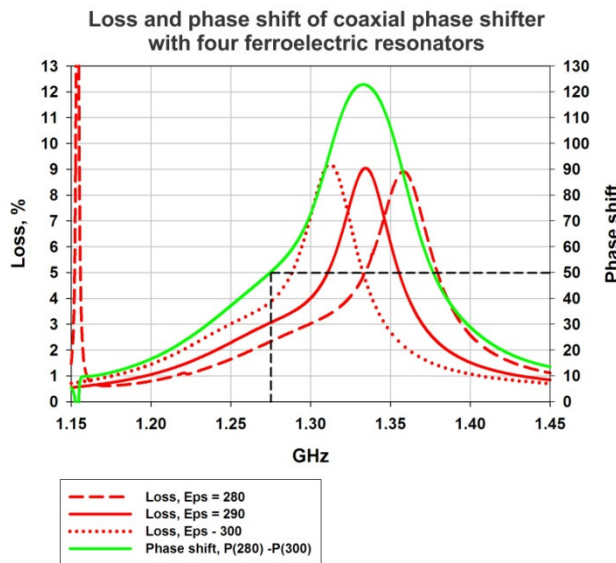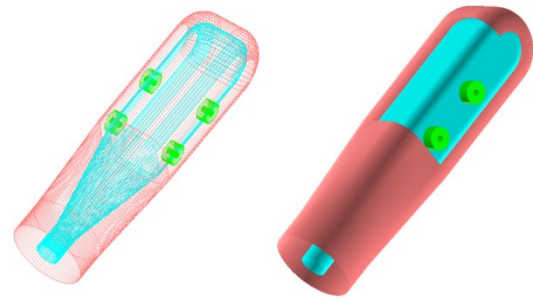

Figure 9: Possible geometry of shorted coaxial phase shifter

Figure 10: Possible way to cascade coaxial phase shifters to increase pulse / average power

Figure 8: Total loss in coaxial phase shifter. Ferroelectric loss tangent is 0.001. Losses in metal walls are taken into account.

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