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Superconducting Transmission Lines with Pulse-Controlled Dispersion

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Abstract **– To control phase velocity in superconducting transmission lines using short electrical pulses, a few approaches are being developed. A new design is developed for left-to-right (L2R) and right-to-left (R2L) tunable transmission lines based on a CPW with embedded paired resonators containing dc-SQUIDs. Experimental layouts are designed according to rules of 2-µm Nb-Al/AlO$_x$-Nb technology for $J_c \approx 0.1$ kA/cm^2 and compared numerically with a scheme-model containing 40 cells at frequencies up to 20 GHz. Characteristic impedance of new dispersive transmission lines is increased above 30 Ohm; a thin-film attenuator is integrated for suppression of standing waves. A stop-band is found for R2L line demonstrating slower phase velocity; this transmission gap is due to effect of shorter wavelength (up to 100 times) reaching electrical length of the paired resonators cell (70 µm). In case of L2R line with faster phase velocity, the transmission band can be almost flat, if simultaneous tuning of frequency for all paired resonators is provided. No negative phase velocity is found in the simulations; however, the increment of differential phase velocity is positive for R2L near edge of the stop-band and negative near the resonance for L2R case.**

I. INTRODUCTION

The microwave metamaterials are artificial structures built as arrays of resonant cells substituting atoms or molecules in solids. Theoretically, they may have negative refraction index due to negative permittivity ε and permeability μ that lead to some interesting features, for example, the Veselago lens ("the super lens"). Such materials are also often named "left-hand materials" [1]. The Veselago lens having flat surface has the ability to go beyond the diffraction limit of traditional lens; no classical lens can focus light onto an area smaller than a square wavelength [2]. In practice, the negative refraction originates from abrupt inversion of phase response near peak of a resonance; this is so-called switching point from normal (right-) to left-hand properties (or vice versa). This effect is loss-limited; it is most pronounced in case of low-loss media, such as superconductor-based metamaterials. Since the phase flip spreads over a narrow frequency range, it is feasible making the resonance tunable. In the case of superconducting metamaterials based on dc-SQUIDs, their inductance depends on magnetic field, thus providing frequency tunablity. It is of great interest to stop (to slow down) the electromagnetic wave in order to enhance transfer of microwave energy to an active media, e.g. to pump a quantum metamaterial [1]. A tunable fast-phase (accelerating) line is useful for distribution of microwaves over area, which exceeds wavelength. Previously we studied coplanar wave-guides (CPW) with embedded chain of dc-SQUID resonators; the tunable rejection band was predicted and demonstrated experimentally [3]. However, there remained a problem of frequency-dependent impedance mismatch of CPW to 50-Ohm environment; by performing a detailed analysis, we suggested using a wide-band 1:10 ratio impedance transformer [4]. To develop a tunable superconducting 2-D Veselago lens, the wide-band operation is needed. Our initial approach cannot improve the impedance matching over band of interest, say 4-14 GHz, if a part of resonators in the CPW is fix-tuned.

II. APPROACHES, DESIGN AND SIMULATION

Here we present a concept of a tunable CPW with constant impedance closer to 50 Ohm; the main idea is employing synchronized tuning of resonance frequencies for both parallel and series (paired) resonators. The tuning of inductances is performed by integrating static and pulsed magnetic field sources right into the structure

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of CPW. The tunable lines are designed as chains of series L2R or R2L cells; their names (abbreviations) formally indicate either inductive (R) or capacitive (L) impedance of the central conductor of the resulting CPW. This approach is illustrated with schemes shown in Fig. 1(a)-(d), where dc-SQUIDs are substituting the inductors. The experimental layouts of cells are shown in Fig. 2(a)-(b). The characteristic impedance of the resulting chain, Z_0, is found numerically via search for a maximum of function $S_{21}(Z_0)$. The value of Z_0=35 Ohm is estimated that mean no large standing wave are expected even in case of direct connection with 50-Ohm line. Nevertheless, a 10-dB attenuator is integrated at input of the chain; the attenuator is a resistive film structure, as shown in Fig. 3(c). The inductance of a dc SQUID, which contains two Josephson junctions, can be expressed as $L_{jj} = \Phi_0/2\pi I_c\cos\varphi$ [5]. Here Φ_0 is the magnetic flux quantum, I_c is the critical current of the SQUID in zero magnetic fields and φ is the superconducting phase difference controlled by the magnetic flux threading the SQUID loop. Choosing equal resonance frequencies for series and parallel resonators from Fig. 1 makes it possible to avoid the stop-band in L2R transmission line found in [3], as demonstrated in Fig. 3(c) and (d).

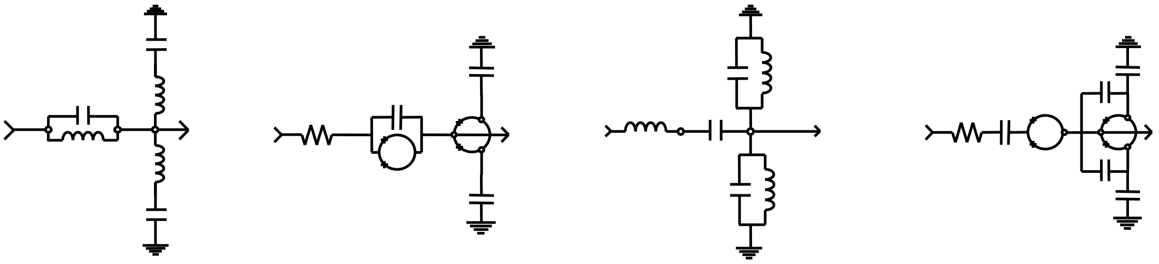
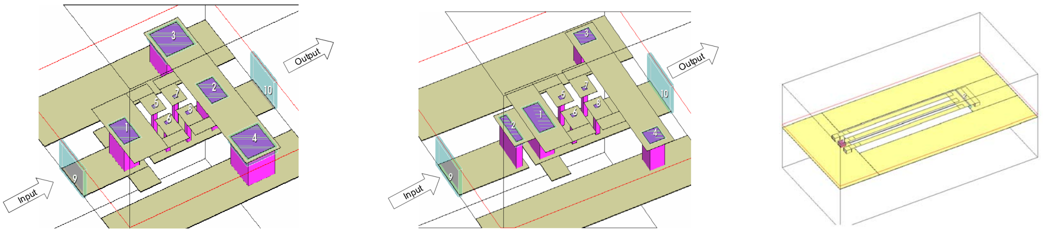

a) b) c) d)

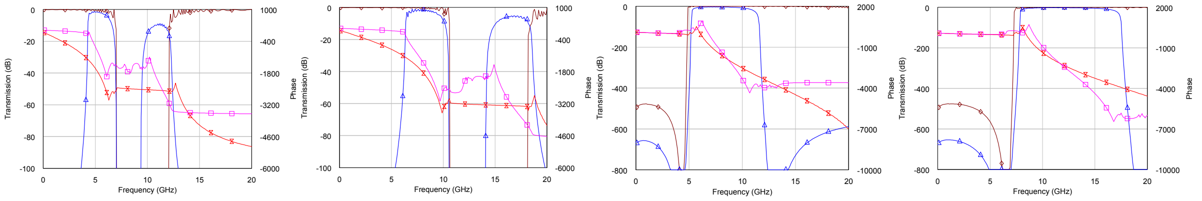
Fig. 1. Equivalent schemes of elementary cells: a) and b) are an ideal right-to-left transmission line (R2L) and its realization with two SQUID-resonators plus attenuator at input, correspondingly; c) and d) are analogous to a) and b) for left-to-right (L2R) line. SQUIDs are shown as circles with two crosses, which substitute Josephson junctions. All schemes assume presence of short section of CPW (Z_0=50 Ohm) in series to the central (horizontal) conductor: 20 µm, 40 µm or 70 µm as it used in Fig. 4 (see below).



a) b) c)

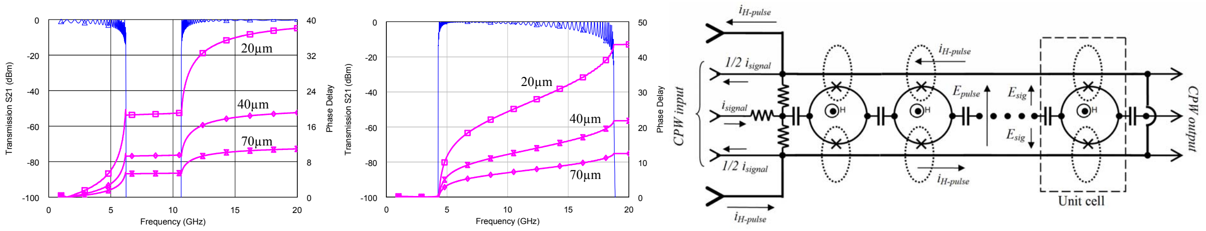
Fig. 2. Electromagnetic layout of schematic cells from Fig. 1: (a) L2R cell with SQUIDs from Fig. 1(b), (b) R2L cell with SQUIDs, (c) thin-film integrated attenuator 10 dB, which is used only at the input of the chain CPW.

Another novelty of the present design is using fewer Josephson junction per cell. The microwave current of the shunting resonator is split between two parts of the ground plane of the CPW, thus improving characteristic impedance of the modified line. We simulated arrays for number of cells N=40 for various magnetic field as shown in Fig. 3. The R and L bands of the transmission are separated by a stop-band in case of R2L. However, the origin of this effect is different from one described in [3]. The transmission stops at a half-wavelength equal to the size of the cell, which sets strong periodic conditions unacceptable for a traveling wave ($Y=\infty$ at resonance), thus supporting only a standing-wave regime. This effect defines the largest value for the slow-phase factor as high as 100 at 10 GHz for the cell size of 70 µm. To analyze dispersion effects, it seems worth using a differential phase criterion, ($\Delta phase/\Delta f$), which is much larger than ($phase/f$), especially at the edge of the stop-band. This effect can be demonstrated also in terms of wavelength delay per 1 mm as presented in Fig. 4(a)-(b). One can see that the achievable delay factor is inversely proportional to the cell size. For the L2R line the faster phase velocity effect can be seen with *lower* value of ($\Delta phase/\Delta f$) at the very middle of the band. The concept of magnetic control of dc-SQUID is illustrated in Fig. 4(c). It is expected that all cells of the array can receive homogeneous magnetic field via the odd mode (slot-line mode) of the CPW. Such magnetic loop is a lumped element up to 1/10 frequency of its first resonance, which is found at 1.25 GHz for 40-cell array, thus defining the pulse duration, τ_{pulse} >10 ns. To synchronize the resonance of the paired SQUIDs, their washers are designed exactly the same, as shown in Fig. 2(a)-(b), providing equal coupling of a magnetic flux.



a) b) c) d)

Fig. 3. Transmission S21 for ideal circuit and layout, both of 40 cells, tuned by magnetic flux (amplitude - left axes; phase in degree – right; blue and magenta - for layout, brown and red - ideal cell); a) and b) are for R2L array at superconducting phase difference φ=0.9 and φ=0.8 correspondingly; c) and d) for L2R at φ=0.9 and φ=0.8. Note the overlap of R and L bands at about 10 GHz due to magnetic tuning of R2L line - a) and b); note phase shift over 2500 degree at 10 GHz - c) and d).



a) b) c)

Fig. 4. Transmission S21 (blue - left axis) and phase shift in wavelength (magenta - right axis). Both arrays R2L (a) and L2R (b) are 40 cells as explained in Fig. 1, but cells are different in length (20, 40 and 70µm). The equivalent scheme (c) is a CPW loaded with SQUIDs and controlled with combination of constant and pulsed magnetic field according to the electrical current flow, as indicated by arrows (only series SQUIDs are shown for simplicity).

VI. CONCLUSION

The suggested synchronous tuning of both series and parallel resonators in CPW demonstrates feasible result. This allows for negligible stop-band effect within the whole transmission band of a L2R line; we found almost perfect band continuity with the characteristic impedance over 30 Ohm and enhanced phase velocity near the right-to-left switching point. The rejection band of R2L medium is naturally set by the electrical length of single cell equal to half-wavelength in the line. The phase velocity reduction up to 1/1000 can be expected for a nano-scale technology. No negative phase velocity is found in the simulations; however, the increment of differential phase velocity is negative for L2R case near the resonance and positive for R2L near edges of its stop-band. The experimental samples are under production, and comparison of experiment and simulation are expected soon.

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