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Tunable Superconducting 2-D Veselago Lens: Conceptual development

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Abstract **– We study properties of a 2D array of crossing superconducting transmission lines containing Josephson junctions. The array is divided into two areas by a straight interface transparent to microwaves: the area of fix-tuned left-handed transmission and the area of magnetic-field-tunable right-handed transmission (LHTL and RHTL). The tunability of the RHTL is provided using SQUIDs, which serve as magnetic field-tunable inductors, thus modifying the microwave dispersion in the line. We demonstrate via EM modeling that the practicable 2D array bearing the interface between LHTL and RHTL areas may behave like an interface of a 2D Veselago lens.**

I. INTRODUCTION

Nowadays interest to metamaterials is growing. Metamaterials are artificial structures, those are consisted of sub-wavelength artificial atoms that form a homogeneous effective medium for the electromagnetic waves. One of the most interesting and important implementations of metamaterials is the design of the Veselago lens. The Veselago lens or “superlens” is made from left-handed medium and comprises two boundaries between right-handed and left-handed media [1]. The most attractive feature of this lens is its flat surface and possibility to go beyond the diffraction limit of a classic lens [2], [3]. It is well known that the properties like permittivity and permeability can be modeled using distributed L-C networks [3]. Since a superlens is symmetric combination of two interfaces, a design development for a half of the superlens bearing only one interface might be sufficient. The interface can be just a virtual boundary within a grid assembly of RHLT and LHLT transmission lines that allow 2D-isotropic propagation of electromagnetic waves within each part of the array as well as across the boundary.

II. DESIGN AND COMPUTER SIMULATION

The 2D array is a lattice of left-handed (fix-tuned) and mixed (right-to-left tunable) transmission lines somewhat similar to described in [4]-[6]. Since our tunable lines contain dc SQUIDs as tunable inductors, which are known for their high sensitive to magnetic fields, the transmission through our 2D array can be changed via application of weak magnetic field *at fixed frequency* of a signal.

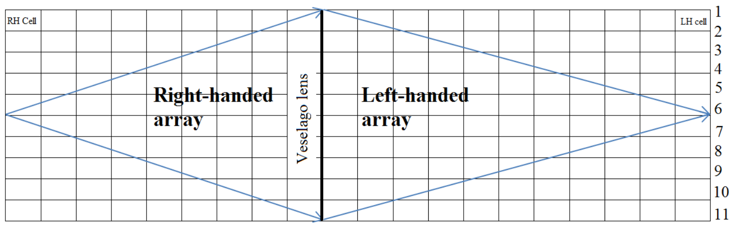

Fig. 1. Concept of the 2D array. The grid presents crossed transmission lines terminated at the edges of the grid with absorbing ports (not shown). The numbered RF ports presented at the right edge of the array are detectors measuring the effect of focusing that is presented with (blue) ray-tracing.

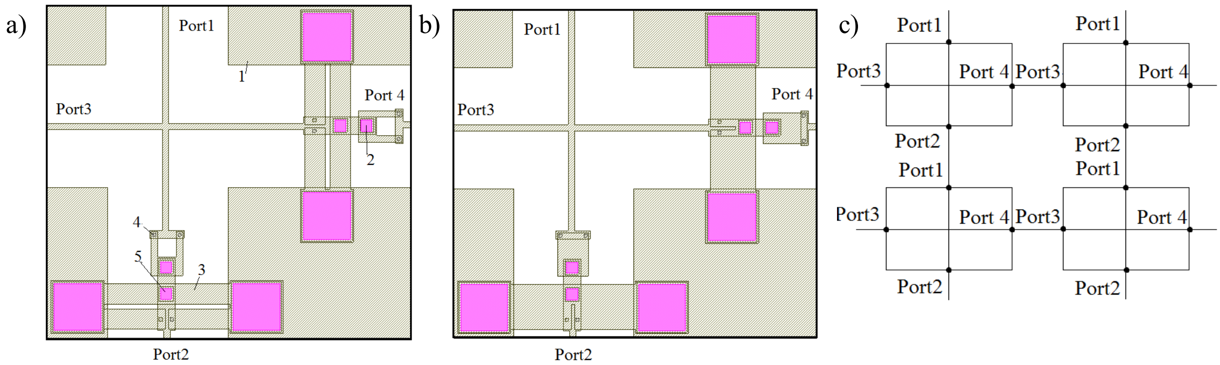

Fig. 2. Layout of 2D Veselago lens modeled with AWR's MWO software. a) Tunable cell of RHTL : 1 - bottom layer, the ground plane for transmission lines, 2 - anodic capacitor at main line, 3 - wiring layer, 4 - two Josephson junctions of the SQUID, 5 - anodic capacitor at shunt. b) LHTL-cell: its legend is the same as for (a). c) Diagram of connections between the cells at the virtual interface.

The most properties of our 1D mixed line are described in [7]. The recent upgrade of the tunable line has at least two advantages. First, there are fewer Josephson Junctions on the main line needed. Since the smaller number of elements, a better spread of parameters of Josephson junctions over the chip can be expected improving the yield. Second, the previous version of the mixed line is designed without a great care of matching to exactly 50 Ω impedance. The detailed analysis showed that the characteristic impedance of the earlier design is variable about typical value of 5 Ω. These lead to much lower measurement accuracy of S-parameters. We tried to fix the problem via implementing a wide-band 5-to-50 Ohm impedance transformer.

The index of refraction, n, is frequency-dependent on capacitance and inductance used in the line [5]. In spite they are similar for both LHTL and RHTL, only the RHTL is tunable via magnetic field as shown in Fig. 3. Unlike in our previous work, the transmission lines contain SQUIDs in both shunt and main line. This solution provides two important conditions. First, both LHTL and RHTL areas of the 2D lens are equal at about zero magnetic fields. Second, the tunable line keeps the same characteristic impedance while tuned over the complete band (no gap present). It is worth to recall the well-known expression for the Josephson inductance [8]:

$$L_j = \frac{\Phi_0}{2\pi I_c \cos\varphi} \qquad (1)$$

Here Φ_0 is the magnetic flux quantum, I_c is the critical current of the Josephson junction and φ is the superconducting phase difference across the SQUID.

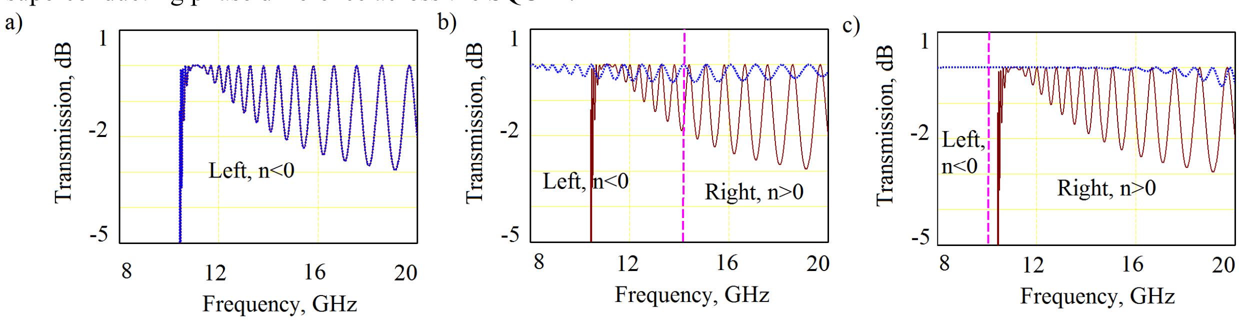

Fig. 3. Simulated throughput (S_{21}): dashed - tunable border between LHTL and RHTL areas, solid - transmission through fix-tuned line of 25 unit cells, dotted - transmission through tunable line of 10 unit cells at following values of *cos φ*: a) $\cos\varphi = 0.8$, both areas are almost the same, both left-handed, no Veselago interface present, b) $\cos\varphi = 0.4$, the interface possible above 14 GHz, c) $\cos\varphi = 0.2$, tunable line is right-handed above 10 GHz, the fixed one remains left-handed, the Veselago interface may exist over most of the transparency band.

At zero field (φ=0) the 2D array is about homogeneous, both left-handed, so no refraction effect is possible. At larger fields, the positive refraction may be expected above 14 GHz for the tunable area, and finally, the most part of operating frequency range is right-handed within the tunable area. One can see from Fig. 3 that in a relatively large magnetic field there is a wide frequency range, where refraction indices of the two areas are opposite, and the LHTL and RHTL parts overlay. The following parameters have been chosen: $C_{LHTR,ML}$=0.5 pF, $L_{LHTR,ML}$= 80 pH, $C_{LHTR,SL}$= 0.5 pF, $L_{LHTR,SL}$= 80 pH; $C_{RHTR,ML}$ =0.5 pF, $L_{RHTR,ML}$= 80 pH, $C_{LHTR,SL}$=0.5 pF, $L_{RHTR,SL}$= 500 pH. The power transmitted to ports 1-11 (Fig. 1) is calculated and shown in Fig. 4. The transmission is always lower than -10 dB because the power is evenly scattered and absorbed with about 40 ports located over perimeter of the emitting area of the 2D array. Under certain conditions, the transmission to ports in the center of the right edge of the array is growing. This can be explained as focusing of the incident electromagnetic wave by the Veselago interface.

a) b)

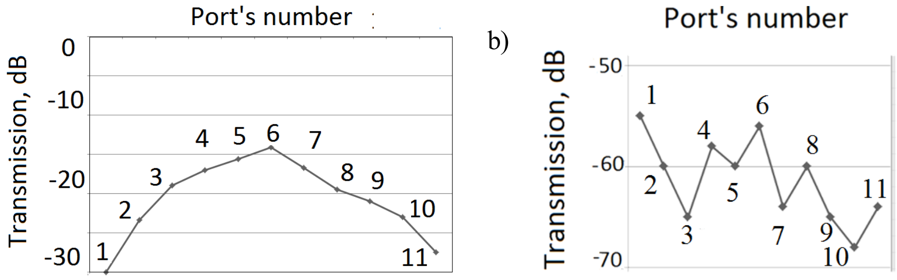

Fig. 4. Anticipated effect of focusing. a) The distribution of power transmitted to ports 1-11 with applied magnetic field in the focused regime; the center is about 15 dB "brighter". b) The distribution of transmission on ports 1-11 without magnetic field - the unfocused (scattered) regime.

III. CONCLUSION

A 2-D array of superconducting transmission lines with Josephson junctions is designed and studied numerically. It is shown, that tunable inductors (SQUIDs) can provide left-to-right-hand tuning of refraction index under application of low magnetic fields. The simulation of the tunable transmission to various ports of the 2D array demonstrated effect similar to focusing and suggested presence of an interface of the Veselago lens. Experimental verification of the simulated results will follow.

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