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Superconducting active metamaterials: Conceptual development

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***Abstract* – We present two concepts for development of active superconducting metamaterials, which can generate and amplify the GHz-range signals. We analyzed two electromagnetic models based on 2-D circuits with Josephson junctions: (i) superconducting oscillator employing ac Josephson effect is formed from a network of underdamped junctions tuned by applied magnetic field; (ii) overdamped junctions arranged into the distributed 2-D amplifying media. To increase the saturation level and optimize the impedance of such media, the series-in-parallel connections are suggested. It is estimated that the high-efficiency oscillator can perform at least up to 0.7 THz with tunability of about 2%; the distributed rf SQUID-amplifier anticipated to operate over the band 8-12 GHz.**

I. INTRODUCTION

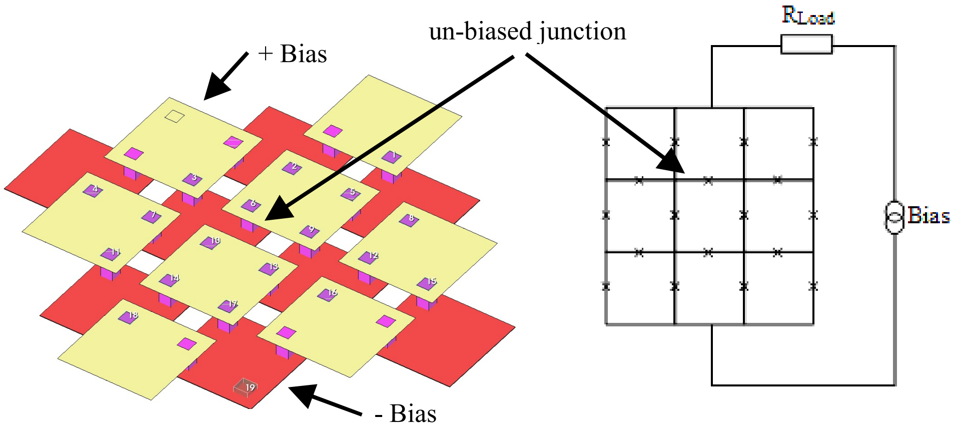
Since the gap energy of a typical superconductor as Nb is about 3 meV only, the natural energy limit of oscillator and amplifiers is applied for both power delivery and saturation, which is usually improved via using arrays of Josephson junctions [1]. The use of 2-D arrays can offer, in principle, unlimited growth of both power and saturation levels. Such 2-D infinitely expandable arrays can be qualified as a kind of superconducting metamaterials as their geometrical structure is not directly related to the operational wavelength. However the series connected and biased arrays of Josephson junctions are known to suffer from unequal frequencies unless they are synchronized via external rf network [1]. A parallel connection suffers from too low rf impedance that complicate the matching network in the high-frequency applications. Effective solution for oscillator is demonstrated with a 2-D network [2, 3]. It was found that the frequency of the oscillator is rather fixed at the internal resonant mode (mode locking regime). No clear model is built till now for the most efficient 2-D oscillator [2, 3]. It was found that coupling with external source for the superconducting SQUID-based quantum amplifier is effective at high-Q resonance (Q>>10), which in turn restricts the bandwidth [4].

II. CONCEPT FOR A THZ-RANGE OSCILLATOR

It is assumed that a 2-D array-oscillator from Refs. [2, 3] can be scaled to higher frequencies up to 1 THz. We have developed an EM-model and calculated the intrinsic resonance of the array. The layout of the model is presented in Fig. 1a; its equivalent schematic is shown in Fig. 1b; the ground plane is not shown for simplicity. To solve the Josephson equations accurately, the port parameters from Fig. 1a can be exported for a lumped element model. The output rf-voltage vs frequency is presented in Fig. 2a. It is possible to see that there are a few (partial) resonance modes with highest frequency near 1 THz. The idea of tuning the resonance arises from possibility to change the inductance of the unbiased (horizontally stretched) junctions and thus tune the general resonant circuit, as it was demonstrated in Ref. [5]. The predicted tunability of the array is demonstrated in Fig. 2b for varying the current of all unbiased Josephson junctions in the range I_c = 10...50 μA.

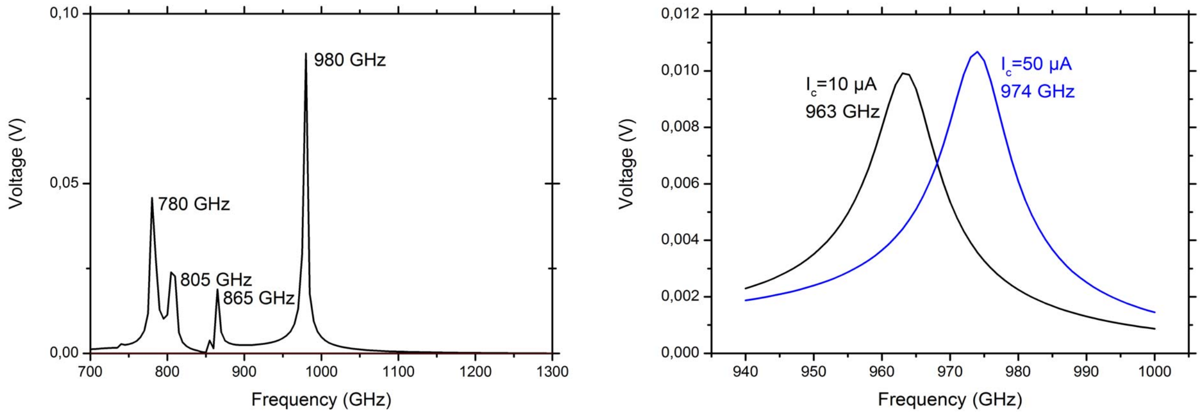
III. CONCEPT FOR A GHZ-RANGE WIDE-BAND AMPLIFIER

To improve the operation of a dc-SQUID sensor shown in Fig. 3a, either the series or parallel connection can be used as presented in Fig. 3b and Fig. 3c. The basic idea is to arrange SQUIDs in mixed mode - as the series-parallel connection shown in Fig. 3d. By proper choice of both the number and the partial absorption of the



a) b)

Fig. 1. Oscillator 2-D array. a) Simplified layout of oscillator array with design rule 1 µm (3-D view); ground plane is not shown. b) Equivalent electrical schematic of the 2-D oscillator ("×" represents a Josephson junction, R_{Load} represents the output transmission line).



a) b)

Fig. 2. Oscillator rf voltage vs frequency. a) Partial resonance modes with highest frequency near 1 THz. b) Tuning of the highest mode of the array via change of critical current of un-biased junctions from Fig. 1b.

individual cells, the 10-GHz range signal traveling through the micro-strip line placed on top of the array can be fully absorbed within certain band. The result of calculation made for 6 by 8 cells array (will be presented elsewhere) is shown in Fig. 4a using scattering coefficient S_{11} and S_{21}. It is essential that the high-frequency resonant modes can be designed far from the bias point. Fig. 4b demonstrates that the resonance, which is unavoidable in such 2-D structure, occurs at reasonably high frequency. The saturation power of this 6 by 8 array can be made - in terms of noise signal, $P=k_BT\Delta f$ - as high as 10^5 K*GHz, that mean the dynamic range of about 60 dB at the physical temperature 100 mK. This temperature applies the limit for intrinsic noise of the device.

IV. Conclusion

Two new concepts for distributed 2-D active superconducting metamaterials - oscillator and amplifier - are tested numerically via linear EM-modeling. The oscillator model reveals the collective resonant modes up to 1 THz; this frequency can be tuned for few percent via control of the inductance of the unbiased Josephson junctions. Such superconducting device can be of great interest for the heterodyne receiver community. The distributed 2-D SQUID-amplifier can offer the instantaneous bandwidth up to 2 GHz along with gain of about 10 dB and the dynamic range up to 60 dB that makes it useful for wide range of applications including radio-astronomy detectors and quantum bit readouts.

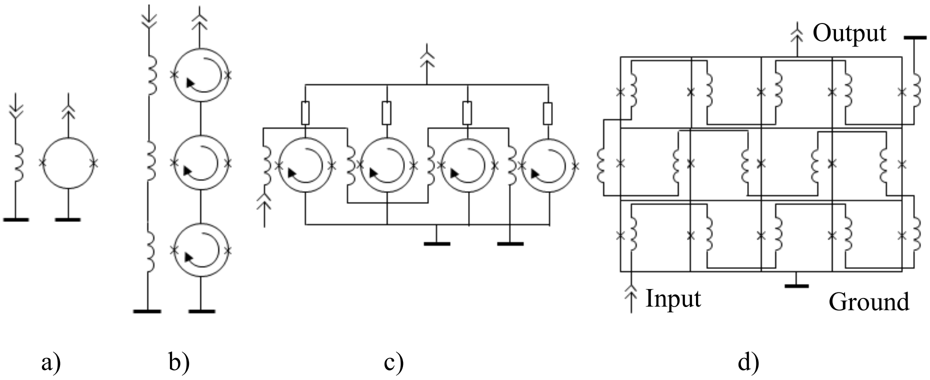


Fig. 3. Equivalent schematics for SQUID-sensors (amplifiers): a) Single dc-SQUID sensor with signal coil. b), c) Series and parallel connections of a few SQUIDs with distributed magnetic coil. d) Series-parallel connection of overdamped Josephson junctions forming 2-D SQUID-like medium controlled with distributed magnetic coil; no ground plane present.

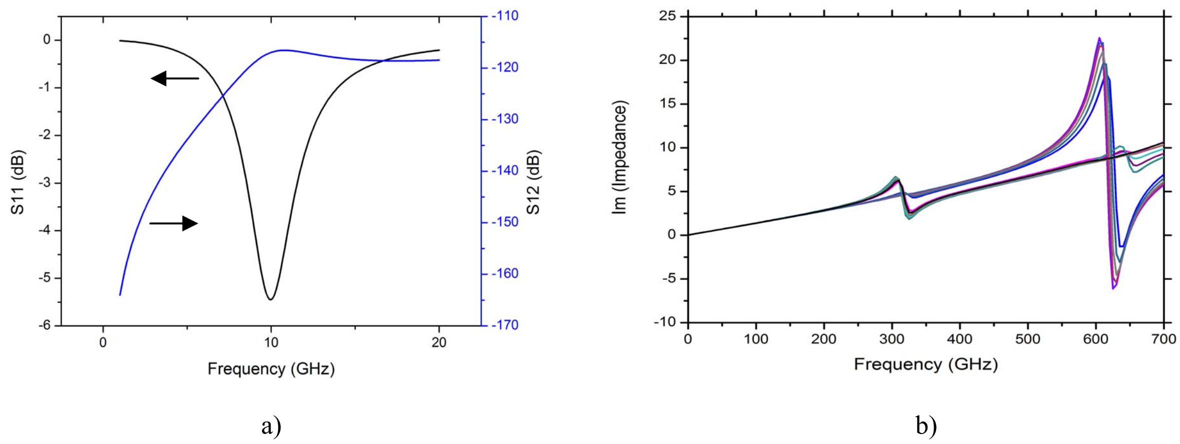


Fig. 4. Calculated parameters for the EM-model from Fig. 4d. a) Scattering coefficient S_{11} and S_{21} responsible for absorption and unwanted leak-to-output transmission, accordingly. b) Embedding impedance calculated for all ports (for all Josephson junctions) demonstrates that no parasitic admittance occurs below bias voltage of 150 μV.

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