CENTRAL FREQUENCY/WIDEBAND QUASIOPTICAL JOSEPHSON OSCILLATOR ARRAYS

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Abstract

In this paper we present new design of quasioptical Josephson oscillators: the Central Frequency/ Wideband design. In this design, tuning structures composed of inductances, radial stubs and quarter wave transformers are integrated with every junction of the array in order to tune out the junction capacitance and match the junction impedance to the antenna impedance for the efficient output power coupling. Each junction feeds an antenna and power from individual junctions is quasioptically combined. We present a variation of the design where a sub-array replaces every single junction of the array. Preliminary results for the array designed for 98 GHz fundamental frequency and fabricated in Hypres Nb/AlO$_X$/Nb technology are presented.

Introduction

In recent years there has been a growing effort within the superconducting research community to develop oscillators based on Josephson junction arrays. Submillimeter Josephson oscillator arrays with power levels of the order of 1μW have been made at Stony Brook [1] and NIST [2]. Two-dimensional array of parallel biased Josephson junctions coupled to small antennas with quasioptically combined output power has been proposed as a promising approach for achieving larger power levels and reasonable radiation linewidths [3]. It has been shown that the performance of these arrays would critically depend on the way the Josephson junctions' capacitances are tuned out [4]. We have proposed arrays with microstrip tuning structures integrated with every junction as potentially the best solution [4]. Because of inherent frequency limitations of tuning circuits, these arrays are designed for one central frequency with the requirement of as large bandwidth as possible. This design will be referred to as the Central Frequency/Wideband (CFW) Design. Here we describe the basic CFW design and one of its modifications, and present preliminary results obtained from arrays fabricated in Nb/AlO$_X$/Nb technology.

Generic CFW array oscillator design

The generic CFW design is presented in Figure 1. MS2 is a very short length transmission line whose inductance tunes out the junction capacitance. A radial stub at the end of MS2 serves as the broadband short. MS1 is the quarter wave transformer that matches the junction impedance to the antenna impedance. That way, all of the rf power produced by the junction is coupled to the

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antenna and radiated in the broadside direction. This design has successfully been used in SIS mixers [5] (see elsewhere in this issue). A detailed account of this and other applicable designs of tuning elements can be found in [6].

We have designed 492 GHz CFW arrays for the following parameters: critical current density $j_c = 4000\ \mathrm{A/cm^2}$, junction capacitance $C_j = 60\ \mathrm{fF/\mu m^2}$ and junction area $A = 7\ \mathrm{\mu m^2}$. The impedance of the log-periodic antenna is around 79 Ω on silicon substrate and is independent of frequency in the designed frequency range. Since there is a basic trade-off between the coupling and the bandwidth, careful design of the tuning elements provides a predicted bandwidth of 80 GHz with 75% power coupling at the central frequency of 492 GHz (Figure 2). The design of the tuning structure is performed in Touchstone [7] with effects of the superconducting kinetic inductance accounted for. The tuning element design values are: $Z_1 = 18\ \Omega$, $l_1 = 62.5\ \mu\mathrm{m}$ (MS1) and $l_2 = 3.5\ \mu\mathrm{m}$, $Z_2 = 15\ \Omega$ (MS2). The 360 junction array is predicted to deliver 20μW of RF power at 492 GHz. A dramatic increase in performance, in terms of both the bandwidth and the coupling is possible with advanced sub-micron and high current density fabrication processes.

Figure 3 shows the fabricated 492 GHz array. It employs 360 log-periodic antennas on a chip 6 mm X 6 mm in size, with integrated tuning structures on one arm of the antenna. All junctions are DC biased in parallel. The array periods are $d_X = 240\ \mu\mathrm{m}$, $d_Y = 264\ \mu\mathrm{m}$. Unfortunately, this fabrication run did not yield working devices because of the minor problem during fabrication. New fabrication runs should be performed in the near future.

Antenna-coupled lumped array

A ready extension of the generic CFW design can be made for arrays at relatively smaller frequencies. Single junction can be replaced by a lumped parallel sub-array of junctions in order to increase the output power. The overall size of the sub-array must be much smaller than the wavelength at the desired operation frequency. Usual tuning structures can be used to tune out the capacitance of the sub-array and to transform the small impedance of the sub-array to the large antenna impedance. If an oscillator is composed of several antennas and sub-arrays biased in parallel, the power from different sub-arrays would be quasioptically combined.

Figure 4a shows a single sub-array oscillator fabricated in $\mathrm{Nb/AlO_x/Nb}$ technology at Hypres, Inc. A compact parallel array of 64 Josephson junctions is placed on one arm of log-periodic antenna on a silicon substrate (Figure 4b). A microstrip transmission line is used as a coupling structure between the sub-array and the antenna. Its electrical length is somewhat bigger than 90° so that the excess portion tunes out the big capacitance of the sub-array and the 90° portion serves as an impedance transformer. Although the bandwidth of this design is rather narrow, it has a nice feature that it works not only at the designed frequency f_0, but at a set of frequencies approximately given by the sequence

$$f_0,\ 3f_0,\ 5f_0,\ \ldots(2k-1)\ f_0. \qquad (1)$$

Array from Fig. 4 was designed for the fundamental frequency of $f_0 = 98$ GHz. The fabrication process parameters were $j_c=983\mathrm{A/cm^2}$, $C_j=38\mathrm{fF/\mu m^2}$, $A=12.2\ \mathrm{\mu m^2}$, $R_N=16.4\ \Omega$. In order to increase the available power, we have placed identical microstrip-coupled sub-array on the opposite arm of the antenna. The two sub-arrays feed the antenna in parallel. The schematic of the electrical circuit is given in Figure 5. The microstrip line was designed with impedance of Z=1.42 Ω and electrical length of 93° at 98 GHz. The measured dc I-V curve of the whole array reveals a series of seven resonant peaks (Figure 6a). A small amount of DC magnetic field was applied along the chip surface to enhance the resonances. When no magnetic field is applied (Figure 6.b) one of the steps (5^{th} counted from V_{dc}=0) has disappeared. The visible critical current (1.25mA , Fig. 6b) is much smaller than about 15mA expected from the size of the quasiparticle current rise at the gap voltage, which we attribute to noise. The approximate frequencies of resonant peaks are inferred from the I-V curve and are given in Table 1 below.

Resonant step #	Frequency [GHz]
1	81
2	129
3	210
4	243
5	356
6	405
7	518

Table 1. Resonant steps from the I-V curve (Figure 6) of the array in Figure 4.

The first step is at the fundamental frequency f_0 = 81 GHz and is down-shifted from the designed 98 GHz value because of the slight discrepancy between the designed and obtained fabrication parameters. Steps #4 and #6 correspond to higher "oscillator" modes given by k=2 and k=3 (1). At these three frequencies, the two sub-arrays work coherently supplying the RF power to the antenna. The remaining resonant peaks roughly correspond to the sequence of modes with resonant frequencies $(2j-1)\frac{f_0}{2}$, where j = 2, 3, 5 and 6 for the steps #2, #3, #5 and #7, respectively. In these modes, one sub-array supplies the RF power to the other sub-array, and practically no power is radiated through the antenna.

From the size of the resonant steps in the "oscillator" modes we estimate that the available RF power is less than a μW. The experiments for coupling the array radiation to the off-chip SIS detector are in progress . For radiated power in the range of μW, a two-dimensional array of parallel biased antenna/sub-arrays should be employed.

Discussion and Summary

We have presented a new Central Frequency/Wideband design of quasioptical Josephson oscillator arrays that effectively deals with the parasitic junction capacitances. Because of the independent tuning of individual junction capacitances, CFW oscillators would tolerate large scattering in process parameters. Further, because of impedance matching between the junctions and the antennas, these arrays would be very efficient sources. The major disadvantage of the CFW design is the size of the unit cell, i.e. much smaller number of junctions can be utilized per given array area, compared to compact 2-D arrays. This disadvantage is offset by the array efficiency. First fabricated arrays show evidence of likely coherent array operation at a set of frequencies. The design promises Josephson submillimeter oscillators of unprecedented performance.

Acknowledgments

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7. *EESOF Inc., Westlake Village*, CA.

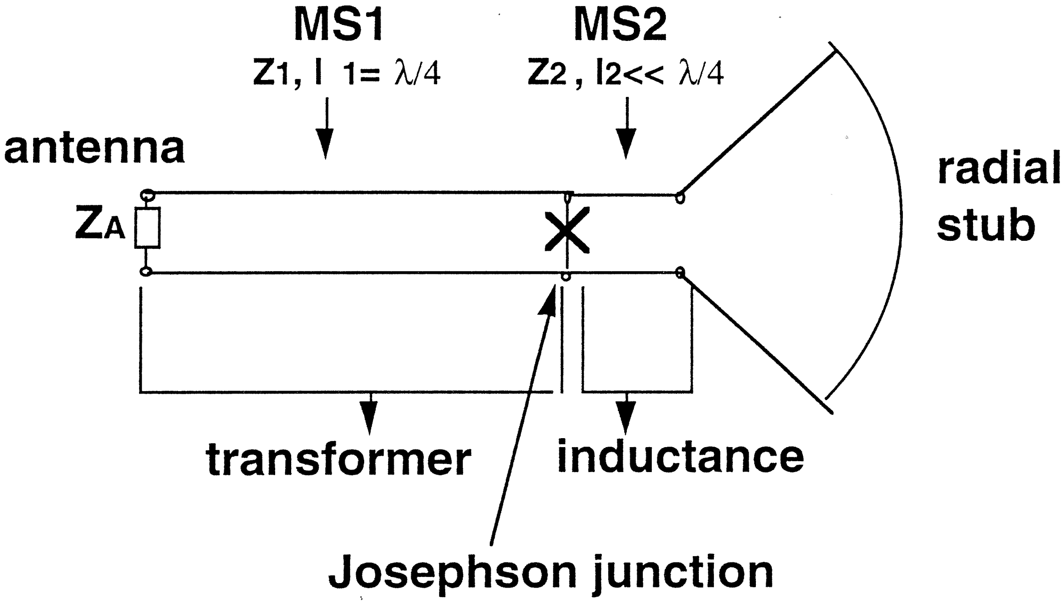


Figure 1. Electrical circuit of the tuning structure for the generic CFW design.

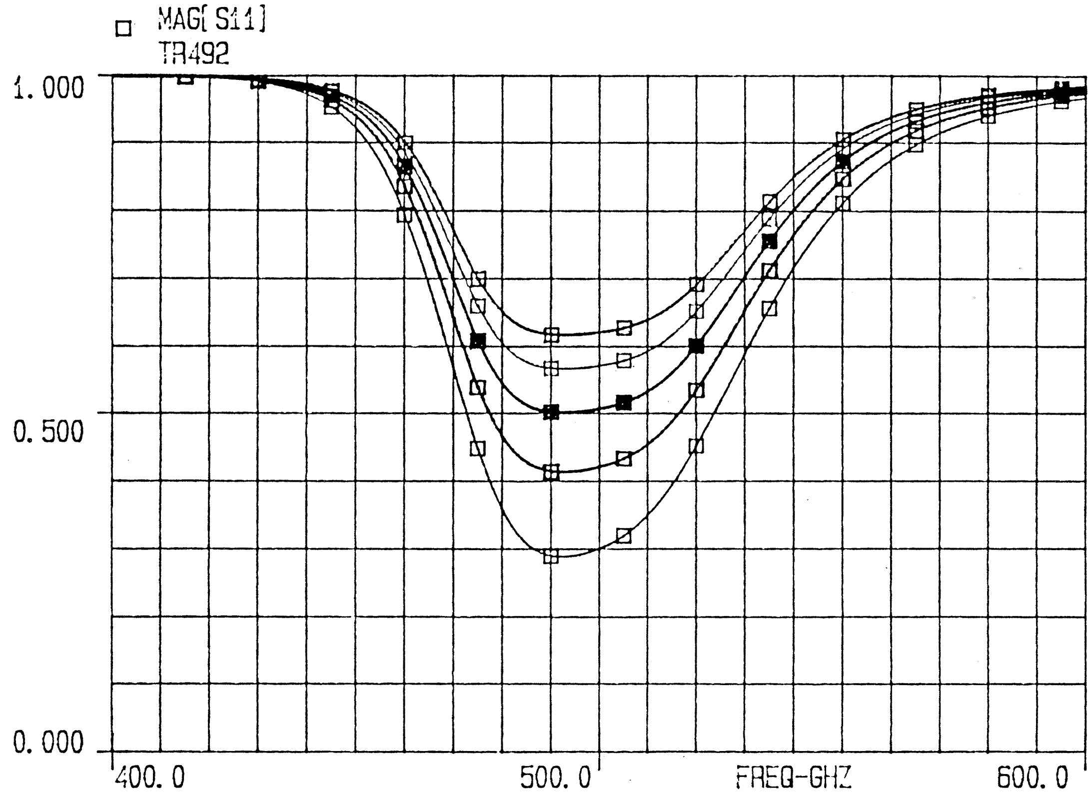


Figure 2. Predicted coupling between the junction and the log-periodic antenna for the 492 GHz CFW design of Figure 1. Different traces are for variation of junction critical current from the designed value: -20% (topmost trace), -10%, 0%, 10% and 20% (bottom trace).

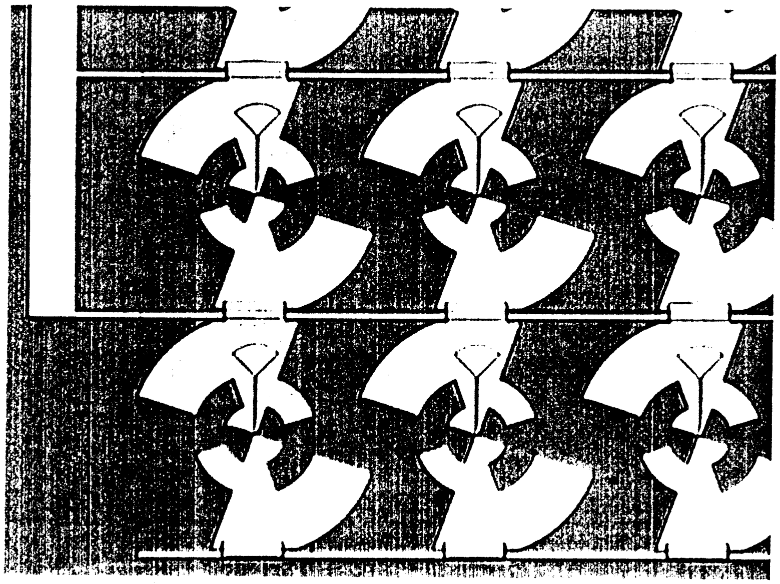


Figure 3. Photograph of a portion of the 360 junction 492 GHz CFW array fabricated in Nb/AlO$_X$/Nb technology.

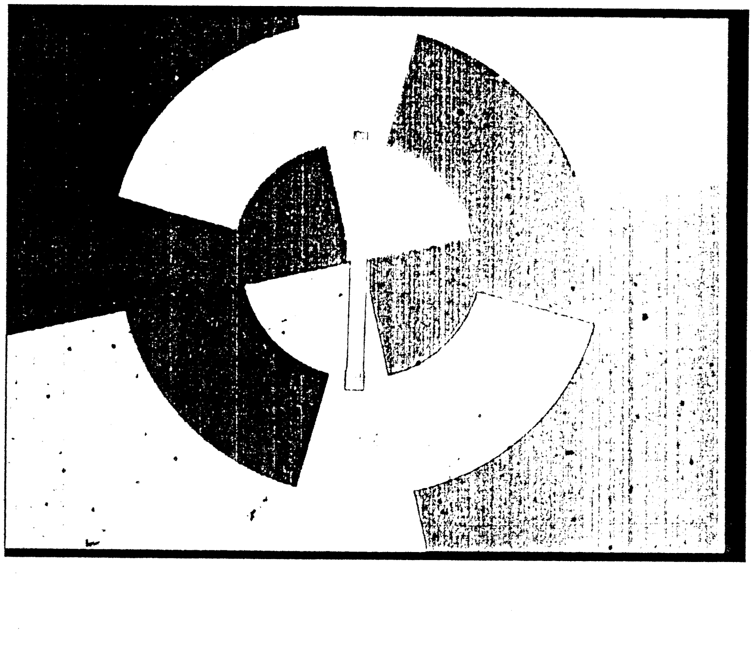


Figure 4a. Photograph of th antenna-coupled 98 GHz lumped array of 128 junctions fabricated at Hypres, Inc.

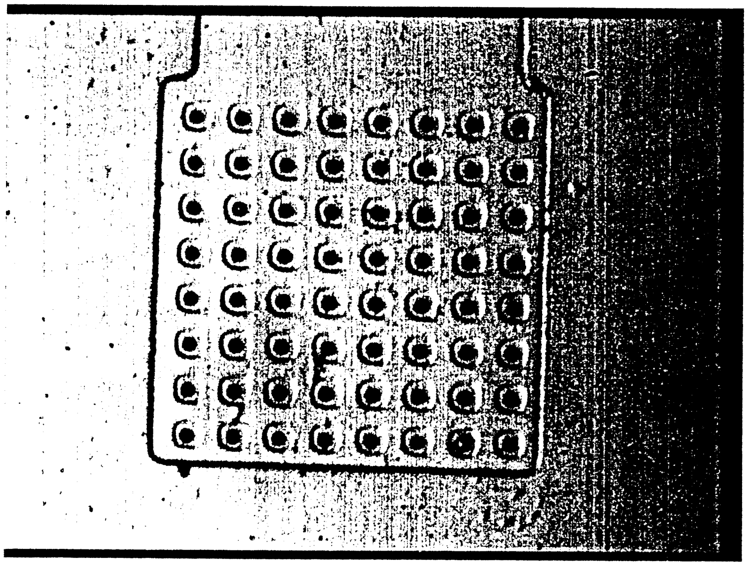


Figure 4b. Detail showing the 8 x 8 sub-array of 12 μm^2 junctions on one arm of the antenna.

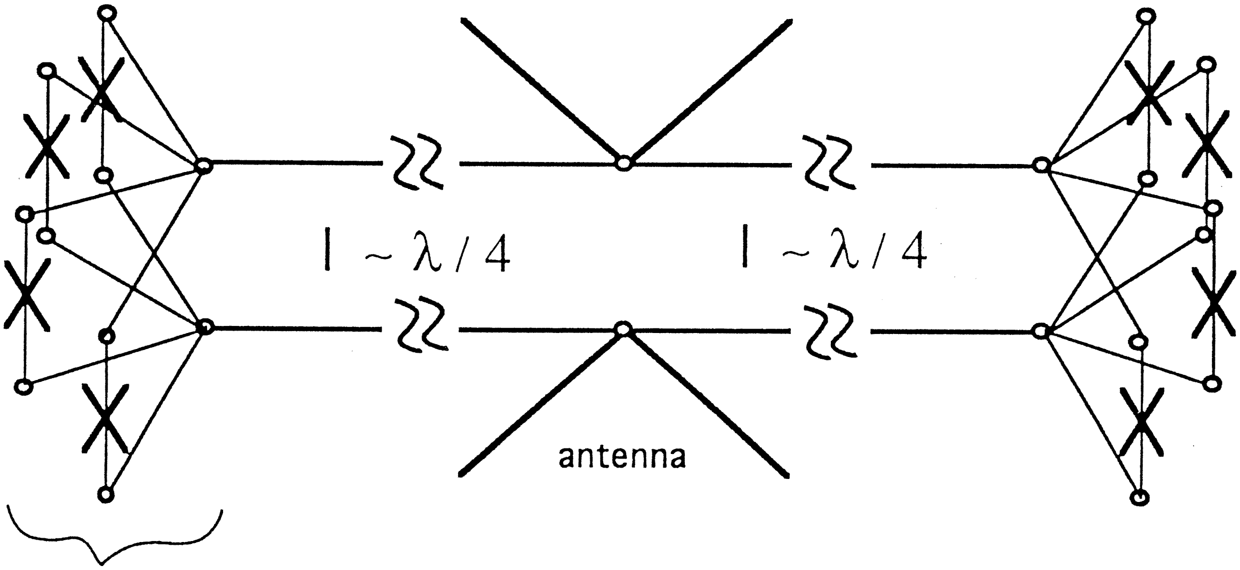
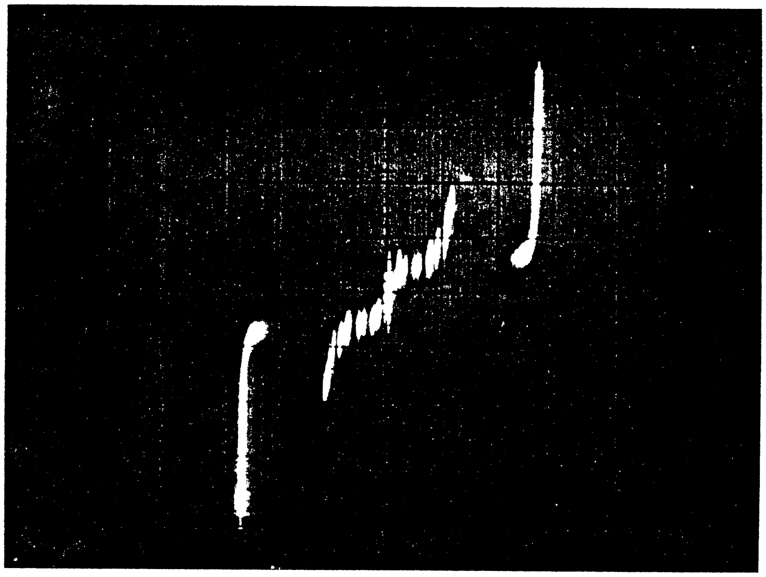
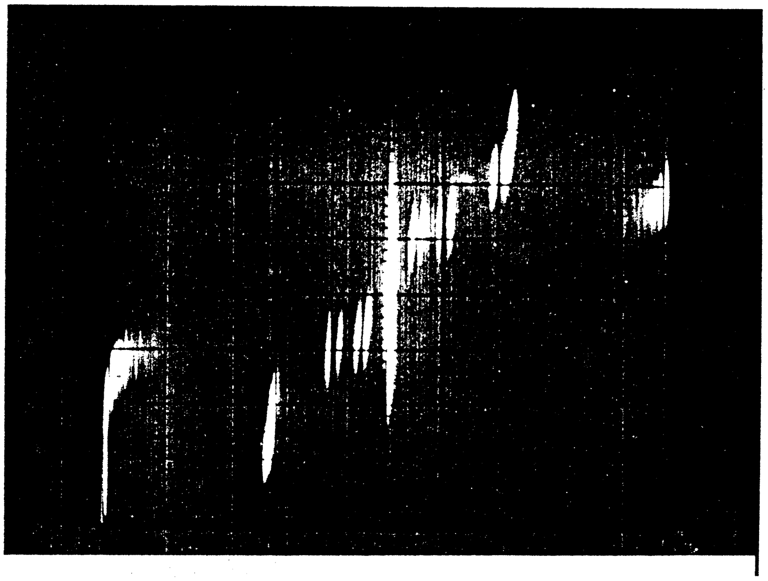


Figure 5. Electrical circuit of the array in Figure 4.



(A)



(B)

Figure 6. Measured dc I-V curve of the array from Fig. 4: (A) with small amount of applied magnetic field (scale: 1mA/div.; 1mV/div.) and (B) with no magnetic field applied (scale: 0.5mA/div.; 0.5 mV/div.).