Fast Resonance Frequency Modulation in Superconducting Stripline Resonator

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Abstract—Fast resonance frequency modulation of a superconducting stripline resonator is investigated. The experiments are performed using a novel device which integrates a hot electron detector (HED) into a superconducting stripline ring resonator. Frequency modulation is demonstrated by both applying dc current or voltage to the HED, and by applying optical illumination, with modulation frequencies of up to 4.2GHz. Potential applications for such a device are in telecommunication, quantum cryptography and biofluorescence.

Index Terms—Parametric excitation, superconducting ring resonator, hot-electron detector, optoelectronics, NbN.

I. INTRODUCTION

Resonance parametric amplifiers are characterized by very low noise, high gain, and phase sensitive amplification. Parametric resonance in superconducting resonators [1] may allow some intriguing applications such as quantum squeezing [2], quantum non-demolition measurements [3], photon creation by the so-called dynamical Casimir effect [4], and more.

Parametric excitation occurs when the resonance frequency of an oscillator varies in time. The first parametric resonance occurs when the excitation is performed periodically at twice the resonance frequency \( f_0 \), namely \( f(t) = f_0 [1 + \xi \cos (4\pi f_0 t)] \) [5]. The system’s response to such an excitation depends on the dimensionless parameter \( \xi Q \), where \( Q \) is the quality factor of the resonator. When \( \xi Q < 1 \) the system is said to be in the subthreshold regime, while above threshold, when \( \xi Q > 1 \), the system breaks into oscillation. Achieving parametric gain where \( \xi Q > 1 \) requires that the shift in the resonance frequency exceeds the width of its peak [6].

The frequency modulation mechanism, we employ here, is based on changing the boundary conditions of a superconducting resonator. This is done by switching a small section of the resonator to a normal state by using optical illumination. The switching time in superconductors is usually limited by the relaxation process of high-energy quasi-particles, also called ‘hot-electrons’, giving their energy to the lattice, and recombining to form Cooper pairs. Recent experiments with photodetectors, based on a thin layer of superconducting Niobium-Nitride (NbN), have demonstrated an intrinsic switching time on the order of 30\( \mu \)s and a counting rate exceeding 2GHz (see [7] and references therein). Resonance frequency shift by optical radiation [8], [9], [10], or high-energy particles [11], [12] (for which the required condition \( \xi Q \gg 1 \) has been achieved) was demonstrated, though no periodic modulation was reported. Resonance frequency tuning [13] and switching [14] as well as optical and microwave signal mixing [15], [16] were demonstrated in normal-conducting GaAs microstrip ring resonators.

In this paper we show experimentally, that resonance frequency modulation, at twice the resonance frequency, is within reach using superconducting microwave resonators. Furthermore, the parametric gain threshold conditions, namely \( \xi Q > 1 \), is demonstrated in a continuous wave (CW) measurement. The experiments are performed using a novel device, that integrates a HED into a superconducting ring resonator. The HED is used as an optically tuned, lumped element, that changes the boundary conditions of the resonator [17], and thus manipulates its resonance frequencies.

In the following section we describe the circuit design and fabrication process. The results section starts with the HED response to applied dc voltage and current, and the resulting effect on the resonance frequencies. These results are followed by a comparison with a theoretical model. Afterwards, the effect of CW and modulated infrared (IR) light on the resonance frequency is described, and fast optical modulation of the resonance frequency is demonstrated.

II. CIRCUIT DESIGN AND FABRICATION

A. Circuit Design

The circuit layout is illustrated in Fig. I(a). The device is made of 8\( \mu \)m thick NbN stripline, fabricated on a sapphire wafer, with dimensions of 34 \( \times \) 30 \( \times \) 1mm\(^3\). The design integrates three components. The first is a superconducting ring resonator and its feedline. Ring configuration is a symmetric and compact geometry, which is generally suitable for applications, which require resonance tuning [13]. The first few resonance frequencies are designed for the S&C bands (2 – 8GHz). The resonator is weakly coupled to its feedline, where the coupling gap is 0.4\( \mu \)m. The stripline width is set to 347\( \mu \)m, to obtain a characteristic impedance of \( Z_0 = 50\Omega \).

The second component is a HED, which is monolithically integrated into the ring structure. Its angular location, relative to the feedline coupling location, maximizes the RF current amplitude flowing through it, and thus maximizes its coupling to the resonator. The HED, shown in Fig. I(b), has a 4 \( \times \) 4\( \mu \)m\(^2\) meander structure, consists of nine NbN superconducting strips. Each strip has a characteristic area of 0.15 \( \times \) 4\( \mu \)m\(^2\) and the strips are separated one from another by approximately 0.25\( \mu \)m [18].
The HED operating point is maintained by applying dc bias. The dc bias lines, forming the third component, are designed as two superconducting on-chip low-pass filters (LPF) with a cut-off frequency of 1.2GHz. As this frequency is lower than the fundamental resonance frequency of the resonator, the intrinsic fields of the resonator are not appreciably perturbed. A cut of 20µm is made in the perimeter of the resonator, to force the dc bias current flow through the HED.

The device, which is top covered by a bare sapphire substrate, is housed in a gold plated Faraday package made of Oxygen Free High Conductivity (OFHC) Copper. Superconducting Niobium ground planes are dc-magnetron sputtered on the inner covers of the package. RF power is fed using a SMA launcher, coupled to the feedline. A dc bias is fed through two π-LPFs, screwed to the package, having a cut-off frequency of 1MHz. IR laser light is guided to the device by a fiber optic cable. A through hole of 1mm in diameter, is drilled in the Faraday package, and a fiber optic connector affixes the tip of the fiber cable at approximately 9.55mm above the HED.

B. Fabrication Process

The fabrication process starts with a thorough pre-cleaning of the sapphire wafer in solvents. We have experienced that the commonly employed process of piranha followed by RCA cleaning substantially reduces the NbN adhesion to the Sapphire wafer. In the next step, 200nm thick gold pads are thermally evaporated through a mechanical mask to form the dc contact pads. The mask partially shadows the evaporation, and thus the pads’ perimeters are smoothed. Epitaxy, 8µm thick, NbN film is then deposited at 700°C using a dc-magnetron sputtering system [19]. Sputtering parameters are summarized in table I and the process itself is further detailed in [20]. Next, an AlN layer of 7nm thickness is in-situ sputtered in N₂ atmosphere at a temperature smaller than 100°C. This layer protects the vulnerable NbN layer during the following fabrication processes and restrain degradation [21]. It has also a functional role, as at cryogenic temperatures, it serves as a thermal conducting layer, which enhances the cooling of the NbN layer. In the next step, the HED meander stripline is patterned using electron beam lithography (EBL). The deposition of a 80nm thick PMMA 950K layer is followed by EBL with the following parameters: 40kV, 15pA, and 2.1nC/cm, corresponding to acceleration voltage, emission current, and line dose respectively. Afterwards, the AlN layer is directly etched through the PMMA mask using ion milling. The remaining AlN layer serves as a mask for the RIE etching of the NbN layer, using low power reactive ion etching (RIE) in SF₆ environment [22]. The remaining PMMA is removed by NMP. The last fabrication step is the patterning of the resonator and the LPFs features. This is achieved by using standard photolithography process. The photoresist development process (employing AZ-326 photoresist developer), also wet etches the AlN layer, while the remaining layer is again used as a mask for the RIE etching of the NbN film.

III. EXPERIMENTAL AND NUMERICAL RESULTS

All measurements presented in this paper are carried out in a fully immersed sample in liquid helium (4.2K). The experimental setup, used for reflection measurements, is schematically depicted in Fig. 2. The samples’ RF feedline is connected to a vector network analyzer using a semi-rigid coax cable. The dc feedlines are connected to a dc source-measure unit using 4-probe wiring. The laser source has a wavelength of 1550nm.

A. DC I-V Measurements

The basic I-V characteristics of the HED meander stripline, shown in Fig. 3(a) exhibit a highly complex hysteretic behavior. Panel 3(a) plots nine current measurements, obtained while increasing the applied voltage (blue), one on top of the other, where each measurement starts at zero voltage and ends at a different maximum voltage, slightly above the voltages \(V_{\text{Cn}}\), depicted in the figure. The corresponding nine current measurements, obtained while decreasing the applied
voltage are also plotted (red). The magenta and black curves correspond to similar measurements, taken while the HED is being illuminated. The measurements for low applied voltages and currents are enlarged in the insets of Fig. 3(a) and (b) respectively, where the finite resistance is due to the contacts.

At panel 3(a), nine, clearly distinguished, abrupt jumps in the measured current are noticed. The number of current jumps corresponds to the number of stripline sections that compose the meander shape of the HED. Each jump is the result of a large increase in the HED resistance due to a transition of one section from the superconducting state to the normal one. This behavior is typical for a superconducting microbridge and is caused by the formation of a hotspot in the bridge area [23]. Each critical voltage $V_{Cn}$, varies, in general, between different scans, indicating thus, the stochastic nature of the transitions between bistable states. The fluctuation $\Delta V_{Cn}$ in $V_{Cn}$, between different scans, characterizes the lifetime of the pre-jump metastable states of the system. The increase in $\Delta V_{Cn}$ at high voltages indicates a decrease in the lifetime of metastable states because of larger temperature fluctuations. The combined results of the increasing and decreasing applied voltage measurements show that large hysteresis is present at all current jumps except for the first one. This observation indicates, that only one section at a time can be biased into subcritical conditions. Furthermore, only the section responsible for the first jump, at $V_{C1}$, doesn’t suffer form hysteresis and thus can repetitively respond to radiation. Probably, the cause for this discretization of the critical current is the non-uniformity in the meander shape of the HED [23], [24]. Our finding clearly shows that the non-uniformity may substantially reduces the effective area of the HED, up to a fraction of 1/9 of its printed area.

The same measurements are repeated while constantly illuminating the HED with approximately 27 nW IR laser. In these measurements the current jumps occur at lower applied voltages, $V_{Cn} < V_{Cn}^{'}$. In addition, $\Delta V_{Cn}$ are substantially widened. Although the decrease in the critical voltage values can be explained by local heating due to the IR illumination, the increase in $\Delta V_{Cn}$, especially at low voltages, imply that photon absorptions cause discrete events that considerably increase the instability of the HED.

Panel 3(b) shows voltage measurements, obtained while increasing the applied current, with (magenta) and without (blue) IR illumination, and while decreasing the applied current, with (black) and without (red) IR illumination. Two abrupt voltage jumps occur at distinguishable critical currents of $I_{C1} \approx 4.2 \mu A$ and $I_{C2} \approx 9.8 \mu A$. IR illumination has a negligible measured effect on $I_{C1}$ and a strong effect on $I_{C2}$ values. All voltage jumps suffer from hysteresis and therefore current bias is an unsuitable method for repetitive radiation detection.

B. DC I-V Effect on the Resonance Lineshape

Fig. 3 shows several $|S_{11}|$ measurements as a function of frequency, in the vicinity of the second resonance mode, for various HED resistance values. For clarity, the resonance curves are vertically shifted upwards, for increasing resistance values. The measurements are obtained while applying variable voltage $V_h$, and the resistance is measured simultaneously

Fig. 2. Setup used for reflection measurements.
with the $|S_{11}|$ data using standard 4-probe technique. The RF input power is set to $-64.7\text{dBm}$, where the resonator is in the linear regime [25]. The inset of Fig. 4 plots the measured HED resistance as a function of $V_b$.

The dependence of the resonance characteristics on the HED resistance $R_{\text{HED}}$ can be described as followed. At zero applied voltage the resonance frequency is $f_{0,V_s} \approx 3.71\text{GHz}$. At very low voltages, as the HED is biased far below critical conditions, its resistance is negligible and its influence on the resonance curve as well. As the resistance increases, the resonance frequency slightly red shifts, and more important, the $Q$-factor is significantly reduced due to dissipation in the HED. This behavior continues up to a point, at $R_{\text{HED}} \approx 1k\Omega$, where the resonance curve can be hardly detected. When increasing the resistance beyond that point the trend of the $Q$-factor changes, the dissipation decreases, and the resonance curve reemerges at a new resonance frequency, $f_{0,V_s} \approx 3.665\text{GHz}$, red shifted by approximately $45\text{MHz}$ relative to its original value. The new resonance $Q$-factor has a value similar to the original one. When further increasing the resistance, the trend of the $Q$-factor continues but no additional resonance shift occurs. The behavior of the $Q$-factor suggests that as $R_{\text{HED}}$ increases, the RF current amplitude of the resonance mode in the HED is reduced, due to current redistribution, and thus the total power dissipation decreases.

Similar behavior, with one major exception, can be observed under applied current, as shown in Fig. 5. The blue, green, red, and cyan curves are taken with subcritical $0\mu\text{A}$, $4.33\mu\text{A}$, and $5\mu\text{A}$, respectively, where $I_{C1}$ is the current at which a first jump in the measured voltage occurs. There are two well defined resonance frequencies, $f_{0,Is} = 3.83\text{GHz}$, and $f_{0,In} = 3.79\text{GHz}$, which corresponds to applied currents below, and above $I_{C1}$ respectively. $f_{0,Is}$, and $f_{0,In}$ slightly differ from $f_{0,V_s}$, and $f_{0,V_n}$ as the two measurements were taken at different thermal cooldown cycles. Low $Q$-factor curves are absent from this measurement because under applied current, the HED can not be biased into intermediate resistance values. At bias currents below $I_{C1}$, the HED has low resistance, which only slightly increases as the current approaches $I_{C1}$. As a result, no resonance shift occurs, and only the $Q$-factor slightly reduces as the current increases. This behavior changes abruptly once the HED resistance crosses a rather low, critical value, $R_C$. A self-sustained hotspot is generated [23], quickly expends, and the HED becomes resistive. $I_{C1}$ is the bias current at which $R_{\text{HED}} = R_C$ is obtained. This thermal runaway causes an abrupt red shift of $\Delta f_0 \approx 40\text{MHz}$ in the resonance frequency. Further increase of the bias current beyond $I_{C1}$ increases the power dissipation and heat generation in the HED. This increases the local temperature and dissipation near the HED, and thus causes $Q$-factor reduction.

C. Resonance Frequency Shift Modeling

To account for our results we calculate the resonance characteristics of our device, as a function of HED resistance. As shown in Fig. 6 the ring resonator is modeled as a straight transmission line, extending in the ±$x$ directions. The HED is represented by a lumped discontinuity, $Z = R + j\omega L$, connecting $x = \pm b$ points together, where $R$ is the resistance, $\omega$ is the angular frequency, and $L$ is the total inductance of the meander shape of the HED. The transmission line has a cut at point $x = a$. The couplings to the RF and dc feedlines are neglected.

The voltage along the resonator’s transmission line is given by a standing waves expression of the form [26]

$$V (x) = \begin{cases} A \cos (\beta x) + B \sin (\beta x) & -b < x < a \\ C \cos (\beta (x - a)) + D \sin (\beta (x - a)) & a < x < b \end{cases}$$

where $\beta = 2\pi f/\sqrt{\epsilon_r}/c$ is the propagation constant along the transmission line, $f$ is the frequency, $\epsilon_r$ is the relative dielectric constant, and $c$ is the speed of light in vacuum.
The resonance frequency as a function of rate data (blue) and the numerically calculated data (red). The resonance frequency, at zero resistance, is the first calculated and measured point. Both curves show calculated data is corrected by measured at different cooldown cycles. In this subplot, the case, a good agreement with the experiment is obtained, and as expected, the measured damping rate exceeds the calculated one, due to losses, which are not taken into account in the model.

A phase transition of $Z$ from superconducting to normal state simultaneously causes changes in its resistive, $\Delta R > 0$, and inductive, $\Delta L > 0$, parts. Both changes contribute to a resonance shift in the same direction. For a very thin superconducting films $\Delta R \gg \Delta L$ resulting in $\Delta Z \approx \Delta R$. Three fitting parameters are used in the model. Best fit results are obtained for $R = 0\Omega$, $Z_0 = 55\Omega$, and $\omega L = 14.5 Z_0$, which leads to $L = 37.3 nH$ for the second resonance mode. $R \ll Z_0$ in the superconducting state, and thus negligible. The characteristic impedance $Z_0$ value is in a very good agreement with the designed value of 50$\Omega$. The calculated inductance $L$ of the meander line at 4.2K without any applied current is 6.05$nH$ [27], but this value is strongly dependent on temperature and current density, so the fit parameter value is in reasonable agreement with the calculated one [27], [28].

Table III summarizes the first three solutions of the boundary condition equation for the two extreme cases of $\Delta R = 0$ and $\Delta R \rightarrow \infty$. Comparing these results to the measured results (taken at two different cooldown cycles), also summarized in Table III shows a good agreement, especially for the second and third modes, for which the resonator is designed.

Fig. 6 shows the second resonance characteristics, resonance frequency and unloaded damping rate $\gamma_2$ of the second resonance mode. The coupling between the different modes and the HED can be characterized by the current amplitude through the HED. The model predicts normalized current amplitudes of 7.3% and 5.7% inside the lumped element, for the second and third modes respectively. This rather weak coupling is the result of the rather high kinetic inductance of the HED. To estimate the coupling of modes two and three to the feedline [29], we show in Fig. 7 the normalized voltage amplitudes, as a function of the ring’s angular location. The calculated normalized voltage amplitudes, at the feedline coupling location, are 71% and 92%, respectively. The voltage amplitudes distribution have, in general, a strong dependence on the resonance frequency, and hence on $\Delta R$, but because of the rather small resonance shift, the voltage amplitudes at the coupling location change by less than 2%.

D. IR Illumination Effect on the Resonance Lineshape

Fig. 8 shows $|S_{11}|$ measurements with (red) and without (blue) IR illumination. The effective IR illumination power, impinging on the HED, is approximately 27nW. The RF input power is set to $-64.7$dBm and the HED is biased with a subcritical dc current of 4.14$\mu A$, which only weakly influences the resonance curve. When the illumination is turned on, the resonance frequency abruptly shifts to a lower frequency.
### Numerical Results

| n  | $f_0$ [GHz] $\Delta R = 0$ | $f_0$ [GHz] $\Delta R \to \infty$ | $\Delta f_0$ [MHz] |
|----|---------------------------|-----------------------------|-----------------|
| 1  | 1.913                     | 1.59                        | 10              |
| 2  | 3.791                     | 3.874, 3.711                | 45, 43          |
| 3  | 5.654                     | 5.634, 5.38                 | 26, 30          |

### Experimental Results

| n  | $f_0$ [GHz] $\Delta R = 0$ | $f_0$ [GHz] $\Delta R \to \infty$ | $\Delta f_0$ [MHz] |
|----|---------------------------|-----------------------------|-----------------|
| 1  | 1.873                     | 1.58                        | 10              |
| 2  | 3.747                     | 3.829, 3.668                | 45, 43          |
| 3  | 5.62                      | 5.608, 5.35                 | 26, 30          |

The new resonance lineshape has the same characteristics as the resonance lineshape measured without illumination under supercritical bias current of $I = 4.39 \mu A > I_{C1}$. This measurement clearly shows that the resonance frequency is sensitive to IR illumination. The measured results in this experiment yield $\xi Q \approx 4.14$.

### E. Fast Modulation of the Resonance Frequency

Fast modulation of the resonance frequency is performed using the experimental setup depicted in Fig. 10. The resonator is excited by a CW pump signal, at frequency $f_0 = 3.71\text{GHz}$, which coincides with the second resonance frequency. The optical signal is modulated at frequency $\Delta f$, using a Mach-Zener modulator driven by a second CW signal, phase locked with the first one. The reflected power is mainly composed of three tones. One is the reflected pump signal at frequency $f_0$. The other two are sidebands, produced by mixing the pump signal and the optical modulation signal, and are found at frequencies $f_{1,2} = f_0 \pm \Delta f$. Occasionally, higher orders of the mixed signals are also detected. The amplified reflected power is measured using a spectrum analyzer, which tracks the $f_1 = f_0 + \Delta f$ tone. No dc bias is needed in this measurement as the RF probe signal also serves as a bias signal for the HED. This bias scheme has two major advantages over the dc bias scheme; first the RF pump bias signal has lower noise, as the $1/f$ and line noises are avoided. Second, the RF bias signal introduces a strong non-linear mechanism [25], [30], which will be discussed in a future publication [31], and produces a high internal gain of the induced optical signal.

The device is not designed for radiation detection. Nevertheless, we find it useful to characterize the response to optical modulation by its noise equivalent power (NEP). Fig. I1 shows the NEP of the device for various optical modulation frequencies. Each NEP data point is derived out of several reflected power measurements in the vicinity of $f_1$, where each measurement is performed with a different pump power, ranges between $-54.7 \text{dBm}$ and $-45.7 \text{dBm}$. The best NEP is measured for a modulation frequency of $\Delta f = 10\text{MHz}$ and equals $38\text{fW}/\sqrt{\text{Hz}}$. A rather low NEP of $370\text{fW}/\sqrt{\text{Hz}}$ is measured for a modulation frequency of $\Delta f = 1.699\text{GHz}$. For this modulation frequency, $f_1$ coincides with the third resonance frequency of the resonator. Higher modulation frequencies than the ones presented in Fig. I1 are also observed, but the measured NEP is relatively poor, mainly due to the bandwidth limitations of the microwave components composing the experimental setup.

### IV. DISCUSSION

Fast modulation of the resonance frequency is experimentally demonstrated. Furthermore, the parametric gain threshold condition is achieved in a CW measurement. The main problem, that currently prevents parametric gain to occur, is the relatively low photon flux that impinges the HED. Due to losses along the optical path, especially the expansion of the Gaussian beam from the tip of the fiber to the HED, the largest
where the results of our optically tunable resonator. Resonance frequency NEP of 38 fW/Hz to the angular resonance frequency numerically extracted by expanding Eq. (1) to first order in unloaded damping rate of the resonance. The damping rate is $\Omega = \sqrt{\frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2}}$.

Moreover, the results are shown to be in a good agreement with the theoretical modeling. The approach used in this device has a great potential of achieving a parametric amplification in superconducting resonators.

**APPENDIX**

**DAMPING RARE EXTRACTION**

The universal expression for the reflection amplitude of a linear resonator near resonance is [2], [33]

$$S_{11} = \frac{i\Omega + (\gamma_1 - \gamma_2)}{i\Omega - (\gamma_1 + \gamma_2)},$$

where $\Omega = \omega_p - \omega_0$ is the pump angular frequency $\omega_p$, relative to the angular resonance frequency $\omega_0$, $\gamma_1$ is the coupling constant between the resonator and the feedline, and $\gamma_2$ is the unloaded damping rate of the resonance. The damping rate is numerically extracted by expanding Eq. (1) to first order in $\Omega$,

$$S_{11} = r_0 + r_1 \Omega + O(\Omega^2),$$

where $r_0$ is the $S_{11}$ value at the resonance frequency,

$$r_0 = \frac{\gamma_2 - \gamma_1}{\gamma_1 + \gamma_2},$$

and $r_1$ is the slope of the imaginary part of $S_{11}$,

$$r_1 = -\frac{2\gamma_1}{(\gamma_1 + \gamma_2)^2}.$$

Note that the extraction of $r_1$ is less accurate for low Q-factor curves, and thus the calculated loss factor suffers from a rather large impreciseness at that regime.

**REFERENCES**

[1] N. V. Fomin, O. L. Shalaevand, and D. V. Shantsev, “Parametric resonance in superconducting micron-scale waveguides,” J. Appl. Phys., vol. 81, no. 12, pp. 8091–8096, Jun. 1997.

[2] B. Yurke and E. Buks, “Performance of cavity-parametric amplifiers, employing kerr nonlinearities, in the presence of two-photon loss,” arXiv:quant-ph/0505018 v1, pp. 1–9, 2005.

[3] B. C. Sanders and G. J. Milburn, “Complementarity in a quantum nondemolition measurement,” Phys. Rev. A, vol. 39, no. 2, pp. 694–702, Jan. 1989.

[4] V. V. Dodonov and A. B. Klimov, “Generation and detection of photons in a cavity with a resonantly oscillating boundary,” Phys. Rev. A, vol. 53, no. 4, pp. 2664–2682, Apr. 1996.

[5] L. Landau and E. Lifshits, Mechanics. New York: Oxford, 1976.

[6] M. A. Golosovsky, H. J. Snortland, and M. R. Beasley, “Nonlinear microwave properties of superconducting Nb microstrip resonators,” Phys. Rev. B, vol. 51, no. 10, pp. 6462–6469, 1995.

[7] G. N. Goltsman, A. Korneev, I. Rubtsova, G. Chulkova, O. Minaeva, K. Smirnov, B. Voronov, W. Sysz, A. Pearlman, A. Verevkin, and R. Sobolewski, “Ultrafast superconducting single-photon detectors for near-infrared-wavelength quantum communications,” Phys. Status Solidi C, vol. 2, no. 5, pp. 1480–1488, 2005.

[8] S. Cho and C.-S. Son, “Modulation of the resonance frequency of superconducting microwave resonators,” IEEE Trans. Appl. Superconduct., vol. 13, no. 2, pp. 3659–3662, Jun. 2003.

[9] ——, “Observation of bolometric optical response in superconducting microwave meander lines,” J. Appl. Phys., vol. 84, no. 10, pp. 5657–5661, Nov. 1998.

[10] M. Tsendlekh, M. Golosovsky, H. Chayet, and D. Davidov, “Frequency modulation of the superconducting parallel-plate microwave resonator by laser irradiation,” Appl. Phys. Lett., vol. 65, no. 22, pp. 2875–2877, Nov. 1994.

[11] P. K. Day, H. G. LeDuc, B. A. Mazin, A. Vayonakis, and J. Zmudzinias, “A broadband superconducting detector suitable for use in large arrays,” Nature, vol. 425, pp. 817–821, Oct. 2003.

[12] R. Wedenig, T. Niinikoski, P. Berglund, J. K. R. Inen, L. Costa, M. Valtonen, R. Linna, J. Salmi, H. SeppaK, and I. Suni, “Superconducting NbN microstrip detectors,” Nucl. Instrum. Methods Phys. Res. A, vol. 443, no. 3, pp. 646–663, Sep. 1999.

[13] K. Chang, S. Martin, F. Wang, and J. L. Klein, “On the study of microstrip ring and varactor-tuned ring circuits,” IEEE Trans. Microwave Theory Tech., vol. 35, no. 12, pp. 1733–1739, Dec. 1987.

[14] T. S. Martin, F. Wang, and K. Chang, “Theoretical and experimental investigation of novel varactor-tuned switchable microstrip rmg resonator circuits,” IEEE Trans. Microwave Theory Tech., vol. 36, no. 12, pp. 1733–1739, Dec. 1988.

[15] J.-C. Lee, H. F. Taylor, and K. Chang, “Degenerate parametric amplification in an optoelectronic GaAs CPW-to-slotline ring resonator,” IEEE Microwave Guided Wave Lett., vol. 7, no. 9, pp. 267–269, Sep. 1997.

[16] G. K. Gopalakrishnan, B. W. Fairchild, C. L. Yeh, C.-S. Park, K. Chang, M. H. Weichold, and H. F. Taylor, “Experimental investigation of microwave-optoelectronic interactions in a microstrip ring resonator,” IEEE Trans. Microwave Theory Tech., vol. 39, no. 12, pp. 2052–2060, Dec. 1991.

[17] D. Saeedkia, A. H. Majedi, S. Safavi-Naeini, and R. R. Mansour, “Frequency and time-varying scattering parameters of a photo-excited microwave meander lines,” IEEE Trans. Appl. Superconduct., vol. 13, no. 2, pp. 510–512, Aug. 2005.

[18] J. Zhang, W. Slyszt, A. Verevkin, O. Okunev, G. Chulkova, A. Korneev, A. Lipatov, G. N. Goltsman, and R. Sobolewski, “Response time characterization of NbN superconducting single-photon detectors,” IEEE Trans. Appl. Superconduct., vol. 13, no. 2, pp. 180–183, Jun. 2003.

[19] G. N. Goltsman, K. Smirnov, P. Kouminov, B. Voronov, N. Kaurova, V. Drakinsky, I. Zhang, A. Verevkin, and R. Sobolewski, “Fabrication of nanostructured superconducting single-photon detectors,” IEEE Trans. Appl. Superconduct., vol. 13, no. 2, pp. 192–195, Jun. 2003.
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