Intermodulation gain in nonlinear NbN superconducting microwave resonators

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We report the measurement of intermodulation gain greater than unity in NbN superconducting stripline resonators. In the intermodulation measurements we inject two unequal tones into the oscillator—the pump and signal—both lying within the resonance band. At the onset of instability of the reflected pump we obtain a simultaneous gain of both the idler and the reflected signal. The measured gain in both cases can be as high as 15 dB.
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In previous publications,[1,2] we have presented and discussed extensively the unusual nonlinear effects observed in our nonlinear NbN superconducting resonators, which include, among others, abrupt jumps in the resonance line shape, hysteresis loops changing direction, magnetic field sensitivity, resonance frequency shift, and nonlinear coupling.[3] These nonlinear effects, as it was shown in Ref. 2, are likely to originate from weak links forming at the boundaries of the NbN columnar structure. In the present work, we examine these nonlinear resonators from another aspect by applying intermodulation measurements, which are considered one of the effective tools for detecting and studying nonlinearities in microwave superconducting devices.[4–12]

The results of the intermodulation measurements of these resonators not only provide an important insight as to the possible nonlinear mechanisms responsible for the observed dynamics,[5,11] they exhibit interesting unique features as well. We show that driving the nonlinear resonator to its onset of instability while injecting two closely spaced unequal tones lying within the resonance band into the resonator results in high amplification of both the low-amplitude injected signal and the idler (the tone generated via the nonlinear frequency mixing of the resonator). In Ref. 13, wherein the case of an intermodulation amplifier based on nonlinear Duffing oscillator has been analyzed, it was shown that intermodulation divergence is expected as the oscillator is driven near the critical slowing down point, where the slope of the device response with respect to frequency becomes infinite. The fact that our NbN resonators do not exhibit Duffing oscillator nonlinearity of the kind employed in the analysis of Ref. 13, but yet show high intermodulation gains in the vicinity of the bifurcation points, suggests strongly that the intermodulation gain effect predicted in Ref. 13 is not unique for the Duffing oscillator, and can be demonstrated using other kinds of nonlinear bifurcations. Moreover, in recent publications by Siddiqi *et al.*,[14,15] where dynamical bifurcations between two driven oscillation states of a Josephson junction have been directly observed, it has been suggested to employ this Josephson junction nonlinear mechanism for the purpose of amplification and quantum measurements.[15]

The intermodulation measurements presented in this letter were performed on a nonlinear NbN superconducting stripline microwave resonator. The layout of the resonator employed having $T_c=10.7$ K is depicted in Fig. 1(a). The NbN resonator film was dc-magnetron sputtered on 34 mm × 30 mm × 1 mm sapphire substrate near room temperature. The thickness of the resonator is 2200 Å. The film was patterned using standard photolithography process and etched by Ar ion milling. The coupling gap between the resonator and its feedline was set to 0.4 mm. The fabrication process parameters as well as other design considerations can be found elsewhere.[1]

The basic intermodulation experimental setup that has been used, is schematically depicted in Fig. 2. The input field of the resonator is composed of two sinusoidal fields generated by external microwave synthesizers and combined using a power combiner. The isolators in the signal paths were added to minimize crosstalk noise between the signals and to suppress reflections. The signals used have unequal amplitudes: one, which we will refer to as the pump, is an intense sinusoidal field with frequency f_p, whereas the other, which we will refer to as the signal, is a small amplitude sinusoidal field with frequency f_p+f, where f represents the frequency offset between the two signals. Due to the nonlinearity of the resonator, frequency mixing between the pump and the signal yields an output idler field at frequency f_p-f. Thus, the output field from the resonator, which is redirected by a circulator and measured by a spectrum analyzer, consists mainly of three spectral components: the reflected pump, the reflected signal, and the generated idler. The intermodulation amplification in the signal and idler is obtained, as is shown in this letter, by driving the resonator to its onset of instability, via tuning the pump power.

In the intermodulation measurements, we limit the signal power to be several orders of magnitude smaller than the pump power, as was assumed in Ref. 13, and require that all of the tones (pump, signal, idler) lie within the resonance band of the resonator during the intermodulation operation.

In Fig. 1 we present an intermodulation measurement applied to the first resonance mode of the resonator (~2.58 GHz), at 4.2 K, where we measured the idler and the reflected tones (pump and signal) as a function of both the transmitted pump power and frequency. The experimental results presented here were obtained while decreasing the pump power gradually at each given frequency. The pump power range was set to include the onset of nonlinear bifurcations of the resonator first mode, which occurs at relatively

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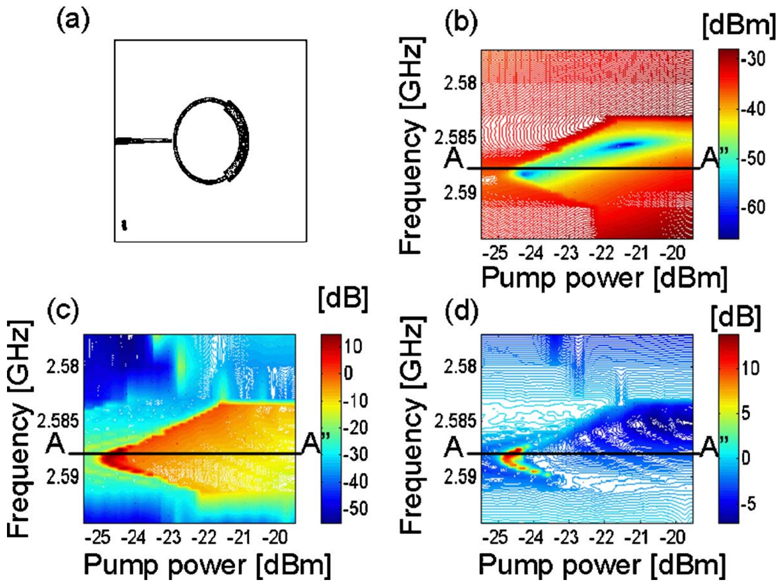

FIG. 1. (Color online) Intermodulation measurement results employing the first mode of the resonator. Plot (a) depicts the layout of the resonator. Plots (b), (c), and (d) exhibit contours of the reflected pump power, idler gain, and signal gain, respectively, as a function of transmitted pump power and pump frequency. The results were obtained while gradually decreasing the pump power. The frequency offset between the pump and signal was set to 2 kHz, whereas the signal power was set to −60 dBm. The cross sections A-A″ are shown in Fig. 3.

low input powers of the order of −25 dBm, whereas the signal was set to a constant power level of −60 dBm. The pump-signal frequency offset f was set to 2 kHz, very much narrower than the resonance band (thus ensuring that all three signals lie within the resonance line shape during the measurement process).

The reason for varying the pump power rather than its frequency to the onset of bifurcation is mostly because the bifurcations along the frequency axis are abrupt,[1] in contrast to the bifurcations along the power axis, which are more gradual. In Fig. 1, plots (b), (c), and (d) show contours of the reflected pump power, idler gain, and signal gain, respectively, as a function of pump power and pump frequency. Large amplifications of the idler and the signal are measured simultaneously as the reflected pump power bifurcates at a given pump frequency, as its power is decreased below some power threshold. These amplification peaks can be better seen in Fig. 3, where we show the idler gain and the signal gain at 2.5879 GHz (A-A″ cross section), plotted on the same axis with the reflected pump power for comparison.

The amplification gain [dB], which is defined as the difference between the idler or signal power at the resonator output [dBm] and the signal power [dBm] at the resonator input (losses in cables and passive devices are calibrated), reaches 14.99 dB at its peak in the case of the idler gain, and 13.91 dB in the case of the signal gain.

In Fig. 4 we show a power-frequency hysteresis of the reflected pump signal, which implies that the nonlinear resonance shape of the resonator, as a two-dimensional function of input power and frequency, is multivalued; therefore, care must be taken in choosing the path in reaching each point in the power-frequency plane. Furthermore, in the forward sweep of the pump, no positive gain has been detected in the idler or signal. This may be partly due to the less steep slopes associated with bifurcations in the forward direction, as seen in Fig. 4(b).

Based on these high gains demonstrated experimentally at $T=4.2$ K (and $f\sim 2.5$ GHz), it is interesting to consider the feasibility of demonstrating some important quantum phenomena using these nonlinear effects in the quantum regime where $\hbar\omega \gg k_B T$ ($T \ll 100$ mK). As in Ref. 13, we consider the mode of operation wherein a homodyne detection scheme with a local oscillator having the frequency of the pump is employed to measure the resonator output. The noise floor of the device is characterized by the power spectrum P of the homodyne detector output, where the only externally applied input is the pump. In the nonlinear regime of operation noise squeezing occurs; namely, P becomes dependent periodically on the phase of the local oscillator ϕ_{LO} relative to the phase of the pump. In particular, for an intermodulation amplifier having a gain larger than unity, as the one described in the present work, the maximum value of

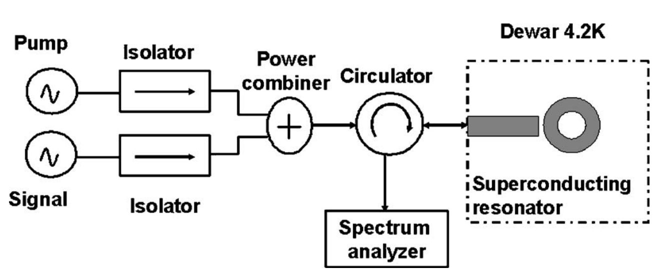

FIG. 2. A schematic drawing of the intermodulation setup used.

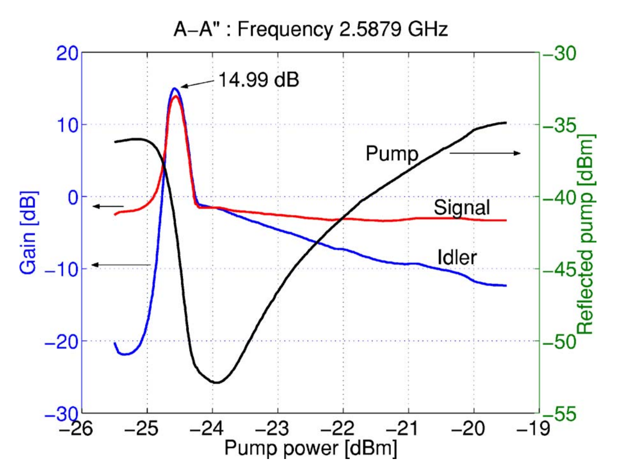

FIG. 3. (Color online) The idler and signal gains at the A-A″ cross section of Fig. 1 are shown as a function pump power. The reflected pump power at the same cross section A-A″ is also drawn on the same axis for comparison. A simultaneous amplification in the idler and signal is measured at the onset of instability of the reflected pump power.

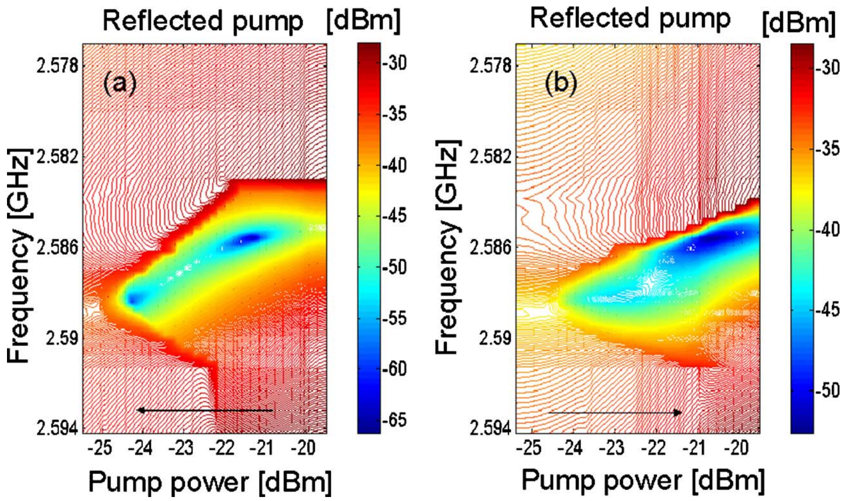

FIG. 4. (Color online) Reflected pump hysteresis during intermodulation operation. Left contour plot obtained while decreasing pump power, right contour plot while increasing pump power.

$P(\phi_{LO})$ may become larger than the value corresponding to equilibrium noise. In the quantum limit, where $\hbar\omega \gg k_B T$, this effect is somewhat similar to the well known dynamical Casimir effect,[16] where a parametric excitation is employed to amplify vacuum fluctuations and to generate photons.

In conclusion, we have measured intermodulation gain in several nonlinear NbN superconducting stripline resonators, at relatively low temperatures ~4.2 K. An intermodulation gain as high as ~15 dB was achieved. Moreover, we showed that the reflected pump power, as well as the signal gain and the idler gain, demonstrate strong hysteretic behavior in the frequency-pump power plane. The intermodulation gain results were found to be both reproducible and controllable, which is a preliminary condition for any practical application. Whereas the underlying physics remains an outstanding challenge for future research, these nonlinear resonators operated as intermodulation amplifiers may be potentially employed, in the future, in generating low-noise microwave signals, signal switching, and even in producing quantum squeezed states[13] and amplifying quantum zero-point fluctuations.

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