

Near-Field Probing of Microwave Oscillators with Josephson Microscopy

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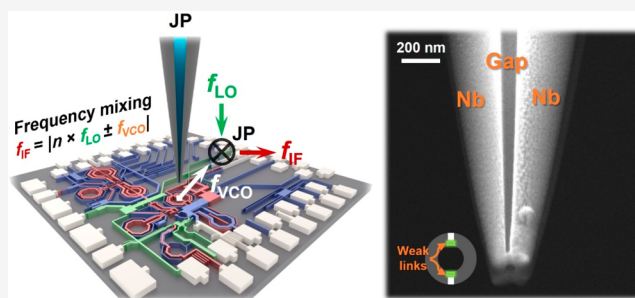
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Supporting Information

ABSTRACT: Voltage-controlled oscillators, serving as fundamental components in semiconductor chips, find extensive applications in diverse modules such as phase-locked loops, clock generators, and frequency synthesizers within high-frequency integrated circuits. This study marks the first implementation of superconducting Josephson probe microscopy for near-field microwave detection on multiple voltage-controlled oscillators. Focusing on spectrum tracking, various phenomena, such as stray spectra and frequency drifts, were found under nonsteady operating states. Parasitic electromagnetic fields, originating from power supply lines and frequency divider circuits, were identified as sources of interference between units. The investigation further determined optimal working states by analyzing features of the microwave distributions. Our research not only provides insights into the optimization of circuit design and performance enhancement in oscillators but also emphasizes the significance of nondestructive near-field microwave microscopy as a pivotal tool in characterizing integrated millimeter-wave chips.

KEYWORDS: Near-field probing, Microwave microscopy, Josephson junction, Frequency mixing, Semiconductor chip



In recent years, complementary metal-oxide-semiconductor (CMOS) devices have been developed toward miniaturization, heightened integration, and high-frequency advancements. It underscored the critical need to effectively characterize the near-field high-frequency electromagnetic distributions of chips under operational conditions. As devices approach the characteristic wavelength of electrons, their behavior tends to exhibit more wave-like attributes, away from classical theories.^{1–4} Simultaneously, as chip integration improves, the reduced distance between devices enhances the coupling of the radiation fields. It transforms the chip performance into a more complex interaction rather than an accumulation of individual functions, particularly with respect to its high-frequency characteristics. The compatibility challenges arising from electromagnetic correlations of CMOS devices are increasingly severe,^{5,6} especially for millimeter-wave chips widely applied in 5G and 6G communications, automotive radar, and security imaging.^{7–9} Traditional techniques for analyzing the performance of high-frequency voltage-controlled oscillators (VCOs) typically involve adding driving circuits on their backends along with additional ground-signal-ground (GSG) pads or on-chip antennas. These approaches not only result in an expanded chip footprint but also introduce unnecessary complexity that may disrupt the normal resonance frequency points of the original VCO circuits. Additionally, the extra circuitry involved leads to the dissipation of valuable high-

frequency energy, further compromising efficiency and performance.¹⁰ Moreover, it lacks spatial resolution capability, preventing accurate determination of the operational status at a specific location on the chip. Hence, there is a pressing need for near-field microwave microscopy, which integrates high-spatial resolution and high-frequency spectrum measurement.

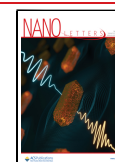
Currently, there are limited methods for nondestructive characterization of high-frequency electromagnetic near-fields upon the operational state of CMOS chips. Traditional scanning near-field microwave microscopes inject external microwaves and interact with the chip through nanotips with coplanar waveguide structure,^{11,12} which can effectively analyze the impedance and dielectric constant of various materials in the chip. However, characterizing the high-frequency distribution generated by the chip itself remains challenging. Although the rapidly advancing NV center sensing technology demonstrates high sensitivity in characterizing microwave fields,^{13,14} its relatively narrow bandwidth and substantial bias magnetic field limit its applicability in characterizing high-

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frequency devices, such as chips operating in millimeter-wave¹⁵ or terahertz frequency bands.¹⁶ Josephson junctions, renowned for their remarkable sensitivity, have been extensively utilized in microwave and terahertz frequency detectors and solid-state sources.¹⁷ Furthermore, they have demonstrated significant advancements in nondestructive imaging of electronic circuits.^{18,19} In recent years, superconducting probe microscopy has exhibited remarkable sensitivity and spatial resolution, particularly in imaging magnetic,²⁰ thermal,²¹ and electrical properties.²² Our newly developed superconducting Josephson probe microscope (JPM) offers an ultra-wideband, passive, and highly sensitive characterizing technique,²³ capable of near-field spectral imaging across the microwave and terahertz bands. It presents promising applications in high-frequency electromagnetic detection in CMOS,^{24,25} spintronic,²⁶ and quantum²⁷ devices.

In this Letter, we employed the JPM to characterize the near-field microwave distribution in a multiband millimeter-wave CMOS chip during operation, as well as high-precision spectral analysis of local points. We observed subtle changes in the chip's operating frequencies under various bias voltages alongside the emergence of side lobes in the frequency spectra. By characterizing its microwave distributions, we revealed parasitic electromagnetic fields generated in transmission lines and frequency division circuits. This information provides a basis for optimizing the electromagnetic crosstalk in the design of the chip. Furthermore, by observing the evolution of the intricate field distribution patterns with varying bias voltages, we also identified the optimal operating voltage for the chip. Using JPM for comprehensive near-field characterization provides significant references for electromagnetic compatibility analysis, defect diagnosis, and performance optimization in millimeter-wave chips.

The technique of JPM involves the fabrication of highly sensitive Josephson junctions at the apex of a nanoscale tip strategically positioned near the sample surface to enable near-field microwave detection. The Josephson probe (JP), shown in Figure 1a, is prepared by depositing Nb films via d.c. magnetron sputtering,²³ exhibiting a diameter of approximately 200 nm. From the SEM image, one can see that Nb film is deposited on both sides and the bottom of the quartz tube, while the middle part remains isolated due to the gap, thus forming two parallel weak-link Josephson junctions at the apex. The experimental setup is illustrated in Figure 1b, where JPM is employed to analyze the semiconductor chip. The acquisition of near-field spectroscopic images and localized spectral information within the chip is realized through a point-by-point scanning procedure. Owing to the necessity of maintaining temperature stability at low temperatures, we sacrifice our imaging efficiency (compared to the conventional microscopy at room temperatures) to achieve the consistency of measurements. The electronic instrument configuration and further descriptions are displayed in the Supporting Information, providing a comprehensive overview of the experimental setup.

The device under test (DUT) is a multifrequency broadband voltage-controlled oscillator (VCO) chip,^{28,29} as illustrated in Figure 1c. Fabricated with 28 nm CMOS technology, this chip operates within the microwave band. The region of interest includes two oscillators labeled VCO_A and VCO_B. The circuit design of these oscillators is presented in Figure 1d. Both VCO_A and VCO_B utilize the principle of parallel inductor-capacitor (LC) resonance

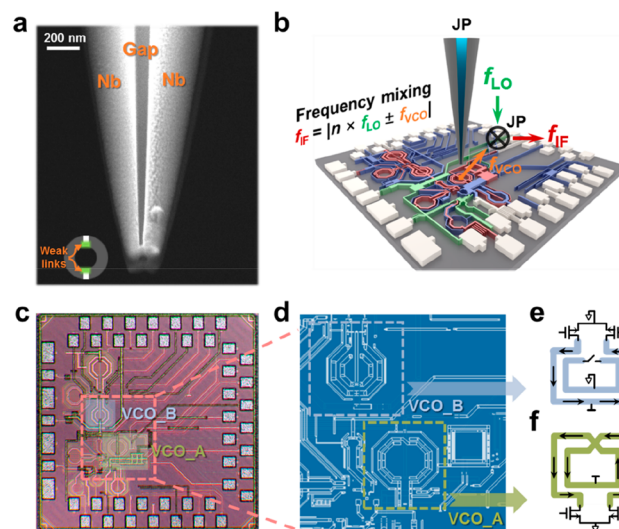


Figure 1. JPM setup. (a) JP's SEM image. The probe consists of two Nb films separated by grooves in the middle. The Josephson junctions are formed at the apex to capture subtle microwave signals. (b) Schematic diagram of probing. The interior of the JPM is mainly composed of a probe and a DUT, providing functions for microwave distribution imaging. Frequency mixing is performed on the probe to conduct the spectrum tracking. (c) Photo of the whole chip. The black dashed line marks the scanning area in this work. Part of the surrounding pins provide bias voltages required for the normal operation of the chip. (d) Circuit diagram of VCOs. The imaging area is divided into two VCO units with different operating frequencies. (e, f) Circuit schematic of VCO_A and VCO_B. Both VCOs share the same LC oscillating principle, with VCO_B adding a switchable transformer to expand its tuning range.

(see the Supporting Information), with their corresponding circuit diagrams presented in Figures 1e and f, respectively. The inductor within the LC tank is realized by a symmetric octagonal spiral structure, while the capacitor employs a cross-coupled configuration. The operating temperatures of JP and DUT are around 3.5 and 10 K, respectively. Owing to the vacuum environment in the cryostat, the small temperature difference between JP and DUT barely has a mutual influence.

First, the transport properties of JP are studied to provide a thorough analysis. As illustrated by the black curve in Figure 2a, its current–voltage characteristics (IVC) display a nonhysteretic feature akin to the superconducting Dayem bridges. The critical current (I_c) of JP is measured to be approximately 13.5 μ A. The a.c. Josephson effect manifests as a phase variation between both sides of the Josephson junction under the application of d.c. voltages. According to the Josephson equation, the relationship between the voltage (V) across the junction and the oscillation frequency (f) of the Josephson current is expressed as $f = 2eV/h$, where e is the electron charge and h is the Planck constant. Typically, the junction's voltage spans from microvolts to millivolts; thus, its frequency range falls within the microwave and terahertz frequency bands. The dc current steps on IVCs upon irradiation of microwaves or terahertz signals, known as Shapiro steps, become apparent once the phase between internal current oscillations and external oscillations is locked. The IVC under 20 GHz microwave irradiation is presented in red in Figure 2a, distinctly showcasing the emergence of Shapiro steps. The corresponding voltage dependence of differential resistances ($dV/dI-V$) is in red in Figure 2c. The

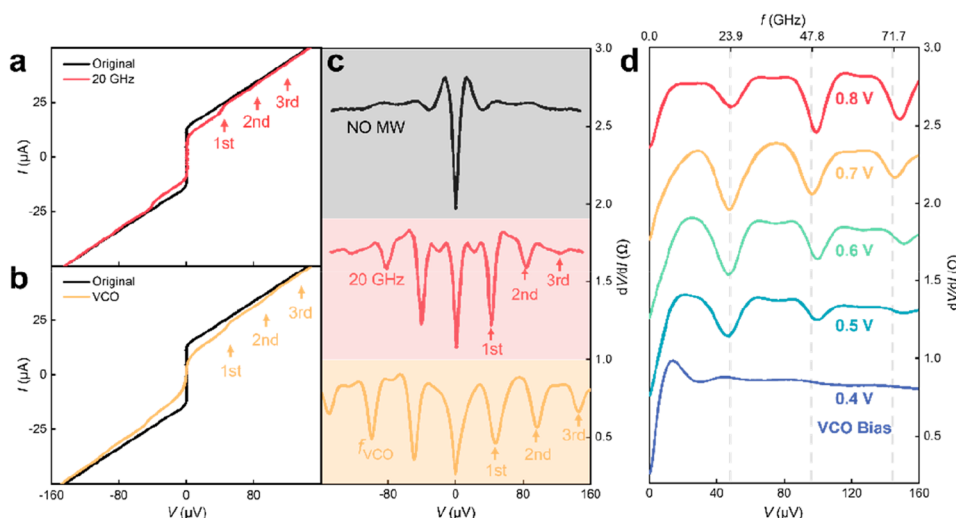


Figure 2. JP's microwave responses. (a, b) IVCs under different microwaves. The black curve represents the original IVC, the red curve represents the response under 20 GHz microwave injection, and the orange curve indicates the response after receiving microwaves from the surface of VCO_A. (c) Voltage dependence of differential resistances. Three colors correspond to different microwave backgrounds in (a) and (b). Dips in curves represent the positions of Shapiro steps. (d) Voltage dependence of differential resistances. The probe exhibits different curves of differential resistances in response to VCO_A's near-field signals when VCO_A is biased by various voltages. The voltages and frequencies of the x -axis are converted based on the Josephson relationship ($f = 2eV/h$).

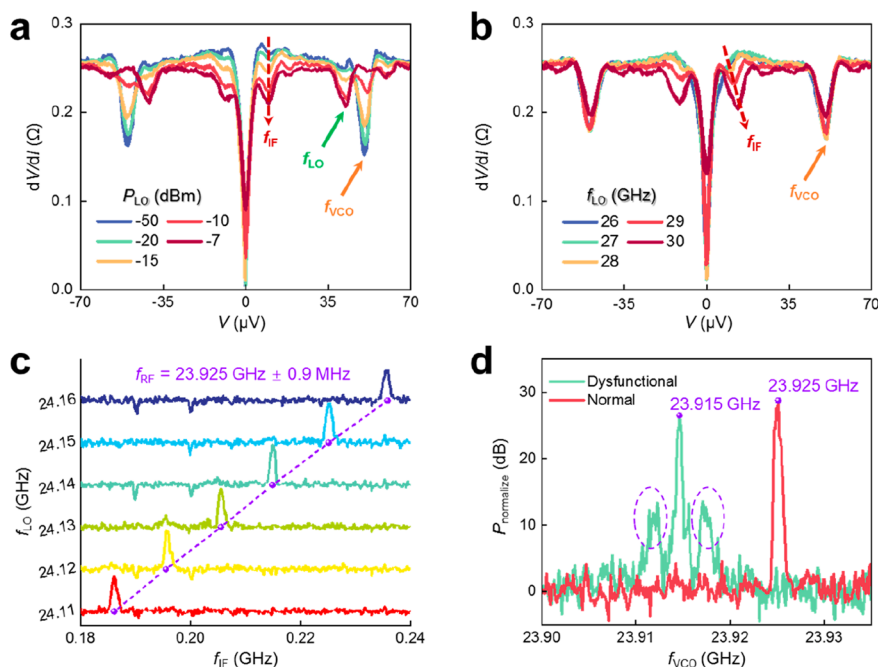


Figure 3. Spectrum tracking. (a, b) JP's IVC under different f_{LO} signals. As the frequency and power of f_{LO} signals change, the differential resistances of JP will generate dips at corresponding positions, and the depth of dips represents the power of each signal. (c) The variation of f_{IF} outputs with f_{LO} signals. Every time the f_{LO} signal of 10 MHz is changed, the frequency of the f_{IF} output shifts accordingly. The center frequency of VCO can be calculated according to the formula $f_{VCO} = f_{LO} - f_{IF}$. (d) Restored spectra of VCO_A. The spectrum of f_{VCO} can be derived in reverse from the f_{IF} output. When VCO_A is in a dysfunctional state, the center frequency shifts and side lobes appear in its frequency spectrum.

positions of Shapiro steps in the IVC align with minima in the dI/dV – V curve, where up to third-order Shapiro steps are observed.

Building upon this, we position the probe near VCO_A while the chip is biased at the voltage (V_{VCO_A}) of 0.70 V. The probe's IVC was recorded and compared with its original IVC, as shown in Figure 2b. It is evident that the high-frequency electromagnetic field emitting from the surface of VCO_A

significantly suppressed the superconductivity of JP. This suppression manifests through the appearance of multiple Shapiro steps on the IVC, similar to those illustrated in Figure 2a. The associated dI/dV – V curve, presented in orange in Figure 2c, distinctly exhibits third-order Shapiro steps. This indicates that the frequency and intensity of the signal from VCO_A are similar to those of the 20 GHz microwave signal. However, it is noteworthy that the dI/dV – V curve of VCO

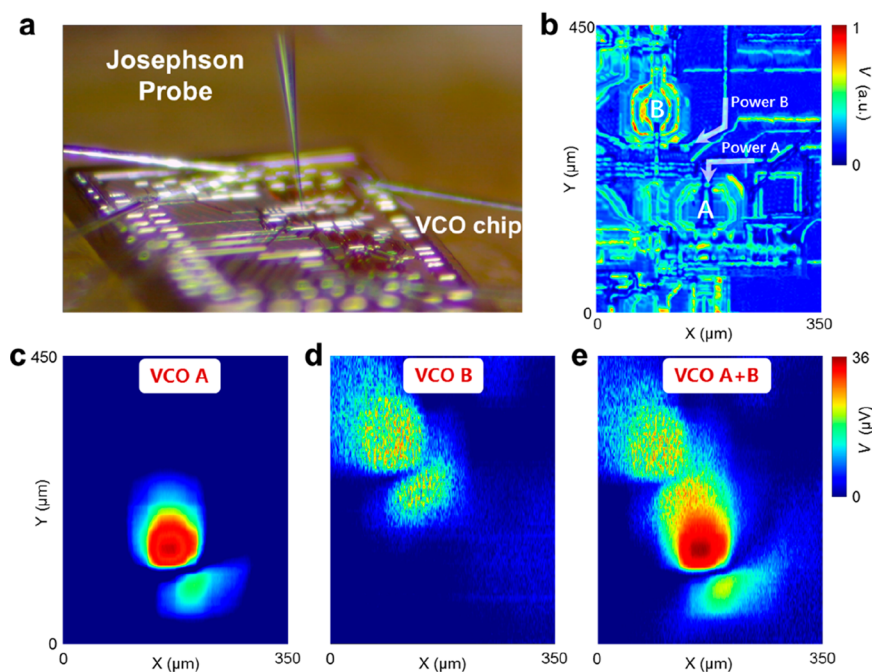


Figure 4. Imaging of two VCOs. (a) Photo of JP and VCOs. After approaching the chip, the scanning is performed at a constant height above the chip surface. (b) Morphology image. A focused laser is applied to image the morphology of the scanning area. The power lines for VCO_A and VCO_B are marked out by white arrows. (c–e) Near-field microwave distributions when VCO_A and VCO_B are on or off. Based on the microwave power distribution, the range of electromagnetic oscillation coverage inside the chip can be obtained. All scale bars are unified into the same range for the sake of clarity. JP is scanned at a height approximately $10\ \mu\text{m}$ above the chip surface, equivalent to a distance of approximately $15\ \mu\text{m}$ from the main inductor. The driving voltages for VCO_A/B are 0.70 and 0.90 V, respectively.

signals exhibits a smoother profile compared to that of 20 GHz signals. This smoother curve suggests the presence of additional low-frequency noises within the chip, further suppressing the superconductivity of JP. Subsequently, we examine the variation of the dV/dI – V curves as V_{VCO_A} is incremented from 0.40 to 0.80 V, as presented in Figure 2d. As V_{VCO_A} increases, a gradual decrease of dV/dI values at the second Shapiro step is observed, ranging from 0.74 to $0.44\ \Omega$. This linear decrease indicates a corresponding gradual increase in microwave intensity. The dips in dV/dI – V curves, marked by gray dashed lines, correspond to the operating frequency of the VCO chip. Notably, the operating frequency remains relatively stable at approximately 23.9 GHz, exhibiting minor fluctuations across the different V_{VCO_A} 's. By analyzing the current–voltage characteristics of JP, we can roughly estimate various working conditions of the VCO chip, providing a reference for specific analysis of VCO's microwave spectrum and distribution.

For VCOs, the precision and stability of their output frequencies are crucial, emphasizing the critical role of spectrum analysis in chip evaluation. Conventional methods used to monitor high-frequency VCO outputs typically require the integration of driving circuits on the backends. However, such approaches increase the chip's footprint and can potentially interfere with other integrated circuitry. The Josephson junction, with its strong nonlinearity,^{30–33} can be used as an excellent mixer in the microwave, even in terahertz ranges. Since we have integrated such a high-performance Josephson mixer onto a nanoscale probe, placing the probe near the chip allows us to perform point-by-point near-field spectrum analysis. Frequency mixing typically involves a local oscillation (f_{LO}) signal, a radio frequency (f_{RF}) signal from the

DUT, and a resulting intermediate frequency (f_{IF}) signal. The f_{LO} signal is generated using a frequency synthesis source and can be coupled to the probe either through a dc-blocking capacitor or radiated via a dipole antenna from space. The f_{RF} signal, originating from electromagnetic oscillations (f_{VCO}) in VCOs, interacts with the f_{LO} signal when coupled on JP. The pronounced nonlinearity of the Josephson current induces mixing phenomena, resulting in the f_{IF} output composed of various frequency signals derived from the summation and differencing of the f_{LO} and f_{VCO} signals. This is expressed by the formula $f_{\text{IF}} = n \times f_{\text{LO}} \pm f_{\text{VCO}}$, where n is a positive integer. The phase and amplitude characteristics of f_{IF} outputs reflect those of f_{VCO} signals, except for the frequency shift. Consequently, a detailed spectral analysis of f_{VCO} signals can be obtained through frequency mixing.

The utilization of JPs for frequency mixing relies on their a.c. Josephson effect. Our initial focus of this work is characterizing Shapiro steps in the IVC of JP generated by signals from various mixing system components. As illustrated in Figure 3a, the minima on the dV/dI – V curves represent positions of Shapiro steps corresponding to multiple signals, indicating dips associated with f_{VCO} signals. As the power of the f_{LO} signal increases, the dips corresponding to the f_{LO} signals rise, while dips linked to the f_{VCO} signals decline. This behavior arises from the interaction between two signals on the JP. Notably, a dip representing the f_{IF} output manifests at a lower voltage, signifying the result of $f_{\text{VCO}} - f_{\text{LO}}$. As the power of f_{LO} signals increases, that of f_{IF} outputs systematically rises, as observed in Figure 3a. On the other hand, with an increase in the frequency of f_{LO} signals, the positions of f_{IF} outputs shift rightward, a phenomenon evident in Figure 3b. Therefore, our observation of changes in the dip values on the dV/dI – V curves confirms

the occurrence of frequency mixing. It is worth noting that the voltage resolution typically resides in the submicrovolt range, resulting in a frequency resolution in the order of hundreds of MHz level following the Josephson relationship.

To fulfill the precision demands of spectrum analysis, a more effective approach involves collecting f_{IF} signals on a spectrograph for detailed analysis, as presented in Figure 3c. Through adjustments of f_{LO} signals at 10 MHz intervals, the corresponding f_{IF} outputs exhibit similar shifts, indicating the fundamental mixing ($f_{\text{IF}} = |1 \times f_{\text{LO}} \pm f_{\text{VCO}}|$). Consequently, the frequency of the f_{VCO} signal is precisely determined with a center frequency of 23.925 GHz and an error range of less than 0.9 MHz. Further enhancement of frequency resolution could be attainable by narrowing the bandwidth of f_{LO} signals or adjusting the band-pass filter of the spectrograph. In addition to accurate frequency determination at any position on the chip, a key technique is the ability to reconstruct the spectral curve from the spectrum of the f_{IF} signal. As shown in Figure 3d, the red curve represents the spectrum of VCO_A operating in the normal state ($V_{\text{VCO}_A} = 0.68$ V), while the green curve illustrates VCO_A in an under-voltage state ($V_{\text{VCO}_A} = 0.18$ V). Under under-voltage conditions, the center frequency of the oscillator exhibits a slight drift compared to the standard state, accompanied by side lobes on both sides of the central frequency. This phenomenon may be attributed to the heightened sensitivity of oscillators to power noise at lower voltage biases. Low biasing voltages contribute to a high signal-to-noise ratio, resulting in an impure spectrum and side lobes in the VCO chips. Moreover, transistors operating at low voltage display nonlinearity, which is susceptible to distortion by truncation. The waveform distortion may introduce additional frequency components into the spectrum. Furthermore, we collect different spectra by varying V_{VCO_A} values (see Figure S6). As V_{VCO_A} is around 0.20 V, the spectrum generally exhibits side lobes, where signals diminish as the voltage increases. Notably, no spectral information is detected within the range of 0.21 to 0.50 V, which may be attributed to the spurious signals with lower intensity and wider bandwidth under nonresonant state. As V_{VCO_A} gradually rises from 0.50 to 0.70 V, we observe a disappearance of stray fields in the spectrum and an increase in the resonance amplitude, indicating a fully resonant status at 0.70 V. Consequently, VCOs typically have an optimal bias point, with deviations in either direction affecting the purity of oscillating frequencies.

Utilizing the nanoscale dimension of JP, we achieve high spatial resolution in imaging near-field microwave distributions from the chip surface. The optical photograph in Figure 4a illustrates the proximity of the probe to the chip. Subsequently, a custom laser lens is positioned parallel to the probe to visualize the chip's morphology and define the scanning range (Figure 4b). It encompasses two VCO chips (VCO_A and VCO_B), as detailed in Figures 1c–f. JP's response to the VCO chip increases rapidly within the range of 50 μm (see Figure S7), indicating that better sensitivity could be achieved if the scanning height is lower. To avoid probe collisions due to the tilt angle of the large scanning area and the roughness of the chip surface, the JP is lifted by 10 μm during imaging.

Microwave distributions on the chip surface under various operating conditions are listed in Figures 4c–e. When only VCO_A is activated, the microwave distribution in Figure 4c reveals circular features due to the inductance realized through an octagonal spiral structure. Signals also extend in the +y-axis direction, potentially originating from low-frequency or even

dc signals in the power supply line from this direction. Notably, signals appear in the right corner, attributed to parasitic fields generated by the connection line from VCO_A to the frequency divider on the right. When it comes to VCO_B in Figure 4d, it shows circular features in the center area similar to those in Figure 4c. A parasitic field distribution in the lower right corner forms an arc-like structure, indicating a strong parasitic electromagnetic field likely associated with the power supply line of VCO_B, influenced by the circuit turning due to deeper wiring in the chip. Figure 4e explores the scenario in which VCO_A and VCO_B are activated simultaneously. The core field distributions of two oscillators remain largely unaffected due to reasonable spatial distance arrangement. However, the parasitic field of VCO_B, originating from its power supply line, overlaps with the distribution of VCO_A caused by its power supply line. In terms of electromagnetic crosstalk, this interference can significantly impact spectrum purity and phase noise, which is crucial for VCO chips serving as local oscillator sources.

A detailed characterization of the near-field microwave distribution from VCO_A is also performed at a reduced tip-sample distance of about 500 nm. By selecting a bias current for JP near I_c , spatial scanning of JP's voltage above VCO_A is conducted, as presented in Figure 5a. The microwave intensity

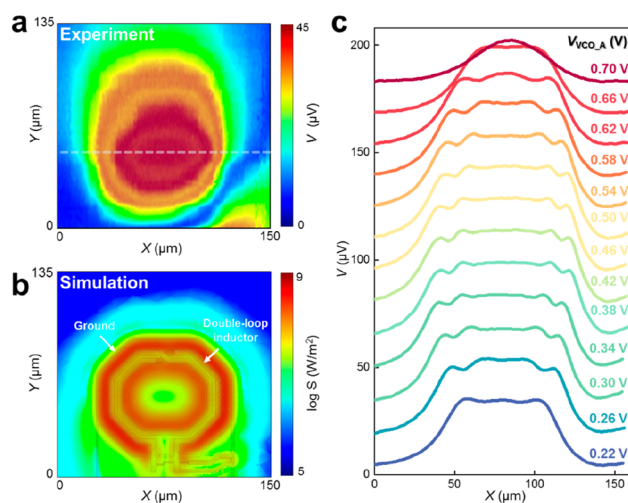


Figure 5. Imaging of the VCO_A. (a) Experimental microwave distribution. JP's voltage signals are tracked spatially during the scanning process when the oscillator is in normal working condition ($V_{\text{VCO}_A} = 0.60$ V). The scanning is performed at a height of approximately 500 nm above the chip surface, equivalent to a distance of approximately 6 μm from the main inductor. (b) Simulated microwave distribution. Based on the HFSS simulation, the distribution of electromagnetic radiation generated by LC oscillation dissipates on the chip surface. (c) Line scan results. The curves are obtained by scanning along the white dashed line in (a), where the color represents the spatial response of JP under different V_{VCO_A} .

forms a circular pattern within the oscillator area. As VCO_A employed a double-loop spiral octagonal structure for the inductor and the outer ground line, the imaging results display a periodic distribution of the circular ring-shaped field strength. To validate this phenomenon, we employed HFSS software for simulation, as displayed in Figure 5b. The simulation illustrates that the distribution of electromagnetic fields is concentrated above the inner coil inductance, exhibiting a size range that is

entirely consistent with the distribution acquired through imaging. This cross-verification reinforces the accuracy of the imaging results. Subsequently, with adjustments of V_{VCO_A} , the probe was scanned along the white dashed line in Figure 5a. The results are presented in Figure 5c. As V_{VCO_A} 's begin to rise, symmetric peaks emerge and become prominent within the curve, aligning with the structure of the inductance. Based on the spectral information (see Figure S6), we suppose that, at low bias voltages, spurious signals are present within the chip and produce corresponding responses due to the broadband detection capabilities of JP. At the optimal operating state ($V_{\text{VCO}_A} = 0.70$ V), the distribution transforms into a circular pattern. This transformation is likely attributed to the resonant signal being effectively transmitted rather than radiated into space, leading to a decrease in the amplitude of detected signals.

In summary, this work is motivated by the need to assess the internal performance and signal crosstalk within the CMOS chips. Utilizing the capabilities of Josephson probe microscopy, we conducted near-field microwave detection to evaluate the spectral characteristics and electromagnetic distributions inside voltage-controlled oscillators. Spectrum tracking reveals intriguing phenomena in chips, including spectrum drift and the presence of stray frequencies, observed in both under-voltage and high-voltage states. Electromagnetic imaging suggests signal interferences between two close units, arising from the parasitic electromagnetic field effect due to the circuit design. These findings hold significant reference for subsequent design optimization and performance enhancement of CMOS chips.

Through the microwave characterization, it is evident that the capabilities of the Josephson probe microscope could also be further optimized. For example, improving the temperature compatibility of DUTs is essential to enable a broader range of applications. This could be achieved by the heat isolation between probes and DUTs, or probes using high- T_c superconductors. When tracking DUT's spectra, the presence of additional f_{LO} signals could potentially introduce parasitic effects that could alter the operational state of DUTs, requiring a thorough evaluation on specific chips to assess these potential impacts. Another feasible approach is to adopt the Hilbert spectroscopy technique³⁴ to achieve nondestructive detection, as well as resolve stray field spectra. With further improvements, Josephson probe microscopy emerges as a straightforward and reliable technique for nondestructive near-field microwave inspection, with further applications in highly integrated millimeter-wave chips.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.4c00454>.

Descriptions about the setup of the Josephson probe microscope and the structure of the semiconductor chip; figures of measurement circuits of the system; cross-sectional structure diagram of oscillators; schematic and layout of oscillators; spectra of oscillators under different bias voltages; and probe responses varying with scanning heights (PDF)

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Notes

The authors declare no competing financial interest.

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