Broad-Band RF Match to a Millimeter-Wave SIS Quasi-Particle Mixer

ANTTI V. RÄISÄNEN, SENIOR MEMBER, IEEE, WILLIAM R. MCGRATH, PAUL L. RICHARDS, AND FRANCES L. LLOYD

Abstract —An integrated superconducting microstrip is shown to be a convenient, flexible, and well-characterized matching element for a superconductor–insulator–superconductor (SIS) quasi-particle heterodyne mixer. The resonant interaction (Fiske modes) between the Josephson oscillations of a voltage-biased junction and the microstrip provides a convenient method for determining the electrical length of the microstrip line. An open-circuited microstrip stub that reflects a parallel inductance across the junction is used to broaden the bandwidth of the RF match of a 30–40-GHz SIS mixer. Measurements with Pb-alloy junctions in a full-height waveguide mixer with fixed mechanical tuning give an instantaneous bandwidth of 10 to 15 percent with a mixer noise temperature $T_M(DSB) = 10 \pm 2.5$ K.

I. Introduction

The SIS MIXER, which makes use of the quasi-particle current in a superconductor–insulator–superconductor tunnel junction has recently surpassed the cooled Schottky-diode mixer as the most sensitive millimeter-wave receiver for radio astronomy [1], [2]. However, compared with Schottky receivers [3], [4], SIS receivers often have a very narrow instantaneous bandwidth, narrow tuning range, or inconvenient tuning requiring several adjustable elements [1], [5]. For spectral line measurements, the narrow bandwidth is not always a critical limitation, but convenient tuning is certainly desirable. A bandwidth broad enough to permit double sideband operation is useful for continuum astronomy or other radiometric applications. Under some operating conditions, care must be taken when using broad-band SIS mixers to avoid saturation due to 300 K noise or nearby strong RF signals. It has been recently shown, however, that the use of series arrays of junctions can increase the saturation threshold of SIS mixers by orders of magnitude without any sacrifice in mixer noise or gain [6].

The question of the optimum embedding impedance for an SIS mixer has not been fully answered. Two regimes can be distinguished by considering the Q value of the tuned junction; the product $\omega_S R_N C_J$ of the signal frequency, the resistance of the junctions in the normal state (or at high voltage), and the junction capacitance. Many workers [5], [7], [8] have used values of $\omega_S R_N C_J > 1$. For this case, the junctions are relatively large, rugged, and easy to fabricate. The large C_J effectively shunts the mixer at harmonic frequencies, but must be tuned out at the signal frequency. This is usually accomplished by an elaborate matching circuit which gives the narrow bandwidth [1], [5], [9]. Good performance [10], [11] has also been obtained with $\omega_S R_N C_J < 1$. This condition is met with small junctions which are relatively unreliable and difficult to fabricate. Optimum mixer performance then requires external circuit elements to suppress harmonic frequencies. Recent calculations suggest that excellent mixer performance can be obtained by either approach [12].

Optimization of either type of SIS mixer requires tuning elements external to the junction, but close enough to minimize stored energy. We focus our attention on the mixers with $1 < \omega_S R_N C_J < 10$. An inductance parallel to the junction will readily resonate out the junction capacitance as is shown in Fig. 1(a), where R_J is the RF resistance of the junction. R_J is typically 1/3 to 1/2 of R_N for a pumped junction. The quality factor of this resonance is low enough that an acceptable bandwidth can be obtained. Although the additional capacitance introduced by the dielectric junction substrate across the waveguide enters the embedding impedance in a more complicated way than the junction capacitance, it is expected that an inductance parallel to the junction will also be helpful in minimizing its effect.

We have employed a simple versatile matching structure consisting of an open-circuited superconducting microstrip which acts as a parallel stub to provide the required inductance across the junction. Such a microstrip can also be used to short circuit the second harmonic response of a mixer. The fabrication of the low-impedance microstrip lines required for this work, as well as their integration with SIS tunnel junctions, has been extensively investigated in the context of the Josephson computer [13], [14]. Another approach which successfully provides the required parallel inductance has been recently suggested by D'Addario [15]. Our method of tuning the junction can be readily applied to mixer blocks with both full-height and reduced-height waveguides and also to junctions in quasi-optical structures.

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A. V. Räisänen was with the University of California, Berkeley. He is now with the Helsinki University of Technology, Radio Laboratory, Otakaari 5A, 02150 Espoo, Finland.

W. R. McGrath and P. L. Richards are with the Department of Physics, Univeristy of California, Berkeley, CA 94720.

F. L. Lloyd is with the National Bureau of Standards, Boulder, CO 80303.

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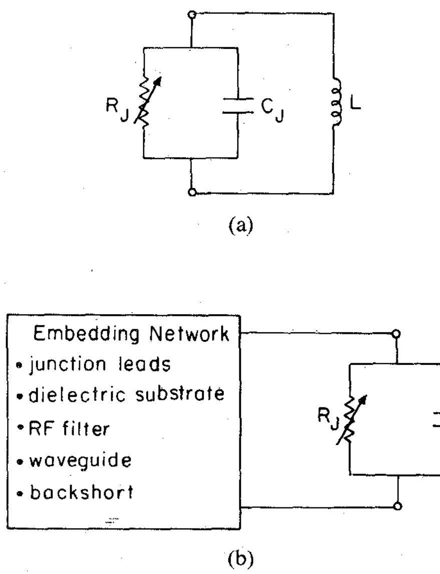

Fig. 1. (a) Equivalent circuit of an inductively shunted SIS junction. (b) Important circuit elements in a typical SIS mixer block without a microstrip stub.

II. The Open-Circuited Stub

The susceptance of an open-circuited transmission line can be written as

$$B_S = \tan(\beta l)/Z_0 \tag{1}$$

where $\beta = 2\pi/\lambda_g$ is the propagation constant on the line, λ_g is the wavelength on the line, l is the length of the line, and Z_0 is its characteristic impedance. In order to resonate a total capacitance C at the signal frequency, we need

$$\omega_S C + \tan(\beta l)/Z_0 = 0. \tag{2}$$

The required stub susceptance can be obtained for $\pi/2 < \beta l < \pi$. For βl in the neighborhood of 0.75 π, this susceptance is only weakly frequency-dependent, so that the stub is approximately equivalent to a lumped inductor. For broad-band operation, it is necessary to choose a value of $Z_0 \simeq (\omega_S C)^{-1}$ so that βl lies in this range.

A theoretical treatment of the properties of superconducting microstrips has been given by Swihart [16]. Gheewala [13] has given convenient expressions for the inductance and capacitance per unit length of line

$$L_l = \frac{\mu_0}{kw}\left[t_d + \lambda_1 \coth(t_1/\lambda_1) + \lambda_2 \coth(t_2/\lambda_2)\right] \tag{3}$$

and

$$C_l = k\epsilon_r\epsilon_0 w/t_d. \tag{4}$$

Here w is the width of the microstrip, λ_1 and λ_2 are the superconducting penetration depths in the ground plane and the microstrip, respectively, t_1 and t_2 are the thicknesses of the ground plane and the microstrip, t_d is the thickness of the insulating layer, ϵ_r is the relative dielectric constant of the insulating layer, k is a fringing factor, and μ_0 and ϵ_0 have their usual meaning in SI units. The characteristic impedance of the line is given by $Z_0 = (L_l/C_l)^{1/2}$, and the wave velocity on the line is $v = (L_l C_l)^{-1/2}$. Since the RF magnetic field penetrates the region $\lambda_1 + \lambda_2 + t_d$, which can be significantly wider than the region t_d of the RF electric field, the microstrips described here are slow-wave structures.

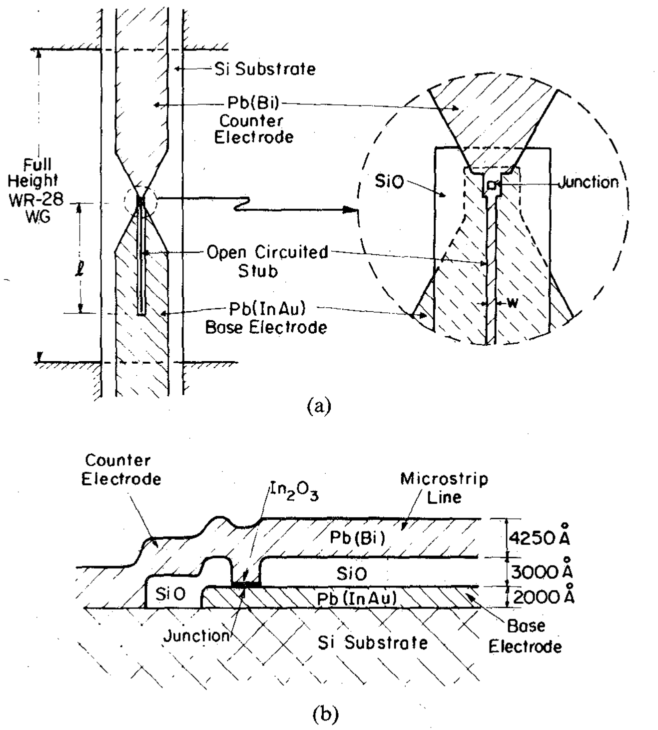

Fig. 2. SIS tunnel junction with parallel open-circuited microstrip stub shown in (a) top view and (b) cross section.

It is a fortunate coincidence that superconducting microstrip stubs with convenient dimensions can simultaneously satisfy several important conditions. The Pb-alloy technology that we use [17] employs an evaporated SiO insulating layer with $t_d = 0.3$ μm. If we choose linewidths of 3 to 5 μm which are easily fabricated by conventional photolithography, then 10 Ω $< Z_0 <$ 20 Ω, which gives small radiation losses and fringing factors $1.2 < k < 1.4$ [18]. For junctions with $\omega_S R_N C_J = 3$, the range of junction RF resistances R_J for broad bandwidth operation is 15 to 30 Ω. Included in this estimate is the assumption that $R_J \simeq R_N/2$. This is a convenient range for impedance matching. Once Z_0 is chosen, then the required line length l can be calculated from (2). Since typical line lengths $l \gg w$, the reference planes for the microstrip are very well defined. The geometry that we have chosen for our SIS mixer junction is shown in Fig. 2.

The ac Josephson effect [19] provides a convenient method for characterizing a superconducting microstrip stub coupled to an SIS tunnel junction. Although the Josephson (pair) tunneling currents do not contribute significantly to the operation of the SIS quasiparticle (single particle) mixer, ac Josephson currents do flow in the junction at a frequency 2 eV/h = 484 MHz/μV, which depends on the bias voltage V, but not on the circuit to which the junction is attached. Evidence for these currents can be seen on the dc $I-V$ curve of a junction which is coupled to a resonant circuit. Structure, whose shape depends on the

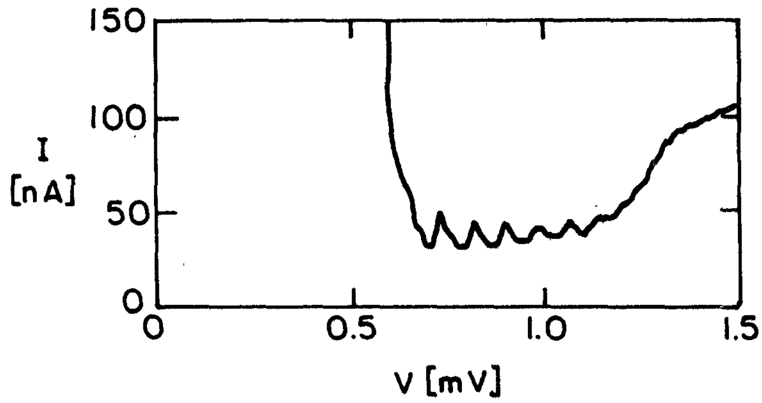

Fig. 3. Peaks on the dc $I-V$ curve of an unpumped junction caused by the resonances of the open-circuited stub. The height of these peaks is typically less than 5 percent of the current rise at the energy gap.

details of both the resonance and the coupling, appears at the voltage which corresponds to the resonant frequency. These effects were first observed for internal resonances of large junctions by Fiske [20]. Later, structure was observed on the dc $I-V$ curves of a Josephson junction due to a strongly coupled external microwave cavity [21]. A detailed theoretical explanation has been given by Kulik [22] and by Eck *et al.* [23].

The microstrip stub shown in Fig. 2 has resonant frequencies which are multiples of ~ 40 GHz. Consequently, we expect to see structure on the dc $I-V$ curve of the junction at multiples of 82 μV. In Fig. 3, we reproduce a portion of the junction $I-V$ curve which shows a series of peaks with this separation.

The last easily observable peak corresponds to a frequency of 568 GHz, which is the $15(\pm 1)$th-order resonance of the fundamental. Superconducting microstrips have very low loss and work well at high frequencies. They are thus well suited to mixer applications at millimeter and submillimeter wavelengths.

The resonant modes on the $I-V$ curve are often small and sometimes difficult to observe. The heights of successive peaks are nearly the same, so a dc load resistance $\leq 10R_N$ should be used. The modes can sometimes be enhanced by the application of an external magnetic field parallel to the junctions surface. Field values which produce a few quanta of magnetic flux $\phi_0 = h/2e = 2\times 10^{-15}$ Wb in the effective junction cross section are useful for this purpose. The effective junction cross section is the product of the length perpendicular to the field and the effective thickness $t_J + \lambda_1 + \lambda_2$, where the junction oxide thickness t_J is much smaller than λ_1 or λ_2. Another technique to enhance the resonant peaks is to apply an audio frequency ac bias and use a lock-in amplifier tuned to the harmonic response to measure the derivative of the $I-V$ curve.

Since the microstrip is RF coupled to the mixer mount as well as to the junction, the spacing of the resonant frequencies will depend upon the embedding impedances. In general, the condition for resonance is

$$B_M + \omega C_J + \tan(\beta l)/Z_0 = 0 \tag{5}$$

where B_M is the susceptance of all the elements in the box in Fig. 1(b). Scaled model measurements of our mixer block show that B_M is capacitive in the signal frequency range from 30–45 GHz and turns inductive and decreases with increasing frequency. The junction leads apparently supply sufficient inductance to effectively isolate the junction and microstrip stub from the rest of the mixer mount at frequencies well above ω_S. In the 300–600-GHz frequency range where the dc peaks are observed, (5) reduces to $\tan(\beta l) = -\infty$. Since the microstrip is approximately nondispersive [16], the peaks are nearly equally spaced in voltage. Observation of these resonant modes on the dc $I-V$ curve is a convenient way to measure the propagation velocity along the microstrip, and thus to determine whether the correct fabrication parameters have been used.

III. Experimental Results

Evaluation of the performance of the superconducting microstrip stub has been carried out using a full-height mixer block which has been described previously [5]. In addition to the tuning elements shown in Fig. 1(b), this block has a screw tuner located $3\lambda_g/4$ in front of the junction. This tuner generally allows a perfect impedance match at ω_S to a single junction SIS mixer without a microstrip stub [6]. Fig. 4 shows the embedding impedance as a function of backshort position at 33 and 36 GHz (a) when the screw tuner is not used and (b) when the screw tuner is adjusted to maximize the gain of a mixer without a stub at 36 GHz. These results were obtained from scaled model measurements at 3–5 GHz [6].

We have used Pb-alloy junctions with area ≈ 8 μm^2, capacitance $C_J \approx 300$ fF, and normal state resistance $R_N \approx 150$ Ω. We thus estimate that $\omega_S R_N C_J \approx 10$ at 36 GHz. The embedding impedance required to match such junctions when pumped with the appropriate local oscillator (LO) power is shown as a shaded region in Fig. 4.

Without either the screw tuner or the microstrip stub, the mixer performance is broad band, but poorly coupled. The double-sideband (DSB) gain measured with a cryogenic hot–cold load [6] is $G_M \approx -10.5$ dB, and the gains of the two sidebands measured with a coherent source are equal within ± 2 dB. The DSB mixer noise is $T_M \approx 14$ K.

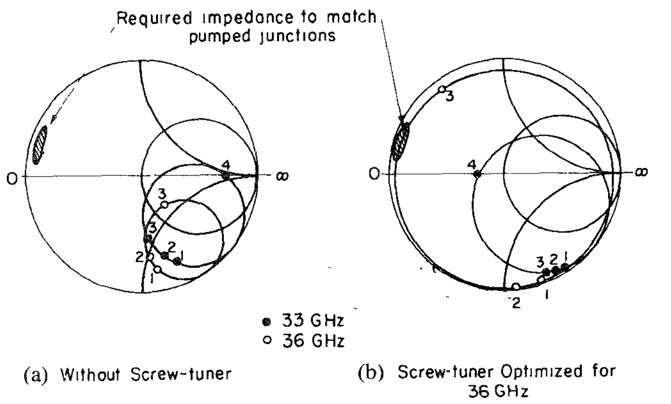

Fig. 4 Smith Chart plots summarizing measurements of the mixer block made on a large scale model at 3–5 GHz. The embedding impedance of the SIS junction is shown as a function of the position of the backshort The numbers give the separation between the junction and the backshort in arbitrary units (a) without the screw tuner and (b) with the screw tuner optimized for match to an SIS mixer at 36 GHz without a microstrip stub. The shaded region shows the impedance required to match the mixer.

The small value of gain is due to the large impedance mismatch at ω_S.

When the screw tuner and the backshort are both adjusted for optimum gain at one sideband (33 or 36 GHz), we typically measure a single-sideband gain $G_M(SSB) \approx -6$ dB. However, the ratio of the gains in the two sidebands is >25 dB in this case. The 3-dB bandwidth is about 200 MHz.

Junctions with parameters similar to those described above, but integrated with the open-circuited microstrip stub illustrated in Fig. 2, were fabricated and tested. The microstrip width was chosen to be $w = 5$ μm. The penetration depths in the ground plane and the microstrip were estimated to be $\lambda_1 = \lambda_2 = 0.135$ μm. The phase velocity was calculated to be $v = 0.3$ c and the line impedance $Z_0 = 10$ Ω.

We estimated the optimum stub length for matching the frequency range from 33 to 36 GHz to be $l = 1.05$ mm from the embedding impedances shown in Fig. 4 and the value $C_J = 300$ fF. Based on this rough calculation, we made junctions with $l = 0.9$, 1.0, and 1.1 mm. Measurement of the dc resonant peaks for these junctions gave a phase velocity of $v/c = 0.30 \pm 0.01$, which is in excellent agreement with the calculated velocity.

We tested each type of stub-tuned junction using the same procedures as for the junction with no microstrip stub, except that the screw tuner was not used. The excellent results obtained with the $l = 1.1$-mm microstrip stub are summarized in Table I(a) and Fig. 5, and compared with the measurements on a junction with no stub. The curves in Fig. 5 show that, for this case, the microstrip stub increases the gain of this broad-band mixer by 4 dB over a 12-percent bandwidth. Conversion gains measured using junctions with the shorter stubs were smaller by 4–15 dB at an LO frequency of 34.5 GHz. This result suggests that the junction capacitance was closer to 200 fF than our original estimate of 300 fF.

TABLE I
COMPARISON OF THE BEST MIXER PERFORMANCE FOR JUNCTIONS WITHOUT AND WITH 1.1-mm MICROSTRIP STUB

a) Broad-Band Performance Without Screw Tuner at 34.5 GHz

Junction	$T_M(DSB)$ [K]	$G_M(DSB)$ [dB]	Sideband Ratio [dB]
Without stub	13.6 ± 3.2	-10.5 ± 0.4	± 2
With stub	7.8 ± 1.2	$-5.2 + 0.4$	2.4

b) Narrow-Band Performance with Screw Tuner

Junction	Frequency (GHz)	$T_M(SSB)$ [k]	$G_M(SSB)$ [dB]	Sideband Ratio [dB]
Without stub	33	6.4 ± 0.7	-4.7 ± 0.3	> 25
	36	—	-7.3 ± 1	> 28
With stub	33	9.1 ± 3.6	-4.1 ± 0.6	13 5
	36	—	-5.7 ± 1	8

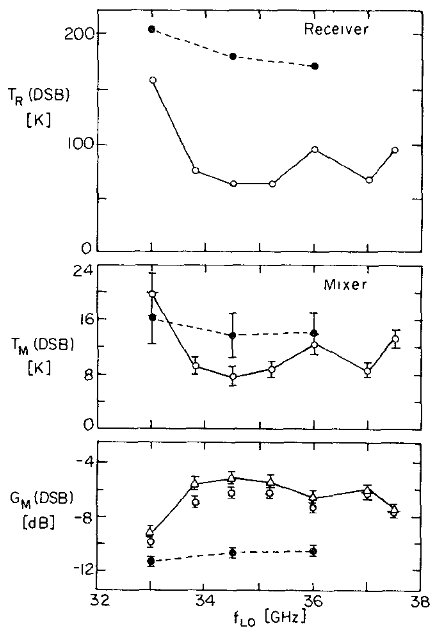

Fig. 5. Mixer and receiver performance measured with no screw tuner and no mechanical tuning adjustments. The solid lines are measured with the 1.1-mm microstrip stub, the dashed lines with no microstrip stub. The open circles give the double-sideband mixer gain including reflection at the IF port due to impedance mismatch. The open triangles give the gain when corrected for this mismatch. The IF frequency was 1.5 GHz.

Also shown in Fig. 5 is the double-sideband receiver noise temperature $T_R(DSB)$ measured for our system using junctions with and without the microstrip stub. These temperatures are referred to the position of our RF variable-temperature load [6] on the input to the mixer and include a contribution from the 1.4 GHz IF amplifier which has $T_{IF} \simeq 13$ K.

In Table I(b), we show results for junctions with and without the microstrip stub, which have been optimized for narrow-band operations at 33 and 36 GHz using both the backshort and the screw tuner. The large error estimates for the upper-sideband gain measurements arise from the fact that the full IF mismatch subtraction procedure [6] was not carried out in this case. Since we believe that the use of both adjustable elements in the mixer block can produce a perfect match for these values of signal frequency, we were surprised to observe that the use of the microstrip stub gives a significant improvement in narrow-band mixer gain. This improvement could be due to a change in the termination of the image, but also to improved termination at the second harmonic.

IV. Conclusions

We have demonstrated that an open-circuited superconducting microstrip integrated with the SIS junction provides an easy way to broaden the RF bandwidth of an SIS mixer. Such a stub can also be used to short circuit the second harmonic response of the mixer and thus improve narrow-band response.

Techniques already used for fabricating SIS junctions can be used to make integrated microstrip lines in a reproducible, well-characterized way. The resulting tunnel junction can be used in full-height, reduced-height, or open-structure SIS mixers, and in other high-frequency applications of superconducting tunnel junctions such as SIS direct detectors, Josephson effect oscillators, and harmonic generators or RF SQUIDS.

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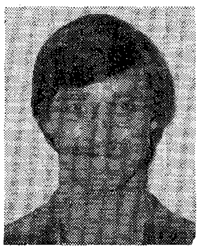
Antti V. Räisänen (S'76–M'81–SM'85) was born in Pielavesi, Finland, on September 3, 1950. He received the Diploma Engineer (M.Sc.), the Licentiate of Technology, and the Doctor of Technology degrees in electrical engineering from the Helsinki University of Technology, Espoo, Finland, in 1973, 1976 and 1981, respectively.

From 1973 to 1978, he worked as a Research Assistant at the Helsinki University of Technology (HUT), Radio Laboratory. From 1978 to 1979, he was a Research Assistant at the Five College Radio Astronomy Observatory (FCRAO) of the University of Massachusetts, in Amherst. From 1980 to 1983, he was a Research Fellow of the Academy of Finland, working mainly at HUT but also for shorter periods at FCRAO. In 1984, he was a Visiting Scientist at the Department of Physics of the University of California, Berkeley. At present, he is an acting Professor of Radio Engineering with HUT. His current research interest is the development of low-noise mixers and other components for millimeter-wave receivers.

Dr. Räisänen was the Secretary of the European Microwave Conference 1982 (EuMC-82). He is also the Counselor of the IEEE Student Branch in Helsinki.



William R. McGrath was born in Oklahoma City, OK, on January 17, 1956. He received the B.S. degree in physics from M.I.T. in 1978 and the M.A. degree in physics from the University of California at Berkeley in 1981. He is currently completing his Ph.D. thesis at the University of California.

His thesis research centers on the device physics of superconducting microwave mixers. He will shortly be joining the Physics Department at the Chalmers University of Technology in Goteborg, Sweden as a postdoctoral Research Physicist.

Paul L. Richards was born on June 4, 1934. He received the A.B. degree in physics from Harvard University in 1956, and the Ph.D. degree in solid-state physics from the University of California, Berkeley, in 1960.

He joined the Technical Staff of the Bell Telephone Laboratories, Murray Hill, NJ in 1960. He left Bell in 1967 to return to Berkeley, where he is now a Professor of Physics. His principal research interests include low-temperature physics, far-infrared spectroscopy, and astrophysics. He has received fellowships from the National Science Foundation, the Miller Institute for Basic Research in the Physical Science, the J. S. Guggenheim Memorial Foundation, and the Alexander von Humboldt Foundation. He has been a Visiting Researcher at Cambridge University, England, the Max-Planck-Institute for Solid State Physics, Stuttgart, West Germany, and the Ecole Normale Superieure, Paris, France.

Dr. Richards is a fellow of the American Physical Society and of the American Academy of Arts and Sciences and a member of the National Academy of Sciences. In 1981, he was named California Scientist of the Year.

Frances L. Lloyd (nee Frances L. Lummis) received the B.S. degree from Duke University (1946) and M.S. degree from the University of Virginia (1948), both in physics. She joined the staff at the Naval Ordnance (now Naval Surface Weapons) Laboratory in White Oak, MD and worked in the Solid State Division for 10 years before leaving to be married.

In 1977, Mrs. Lloyd went back to work, this time at the National Bureau of Standards in Boulder, CO. She is with the Cryoelectronic Metrology Group and fabricates, from drawing board to finished chip, superconducting microcircuits using Josephson technology. She also frequently works with guest workers interested in learning and using the process.