Millimeter-Wave Double-Dipole Antennas for High-Gain Integrated Reflector Illumination

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Abstract—**A double-dipole antenna backed by a ground plane has been fabricated for submillimeter wavelengths. The double-dipole antenna is integrated on a thin dielectric membrane with a planar detector at its center. Measured feed patterns at 246 GHz agree well with theory and demonstrate a rotationally symmetric pattern with high coupling efficiency to Gaussian beams. The input impedance is around 50 Ω, and will match well to a Schottky diode or SIS detector. The double-dipole antenna served as the feed for a small machined parabolic reflector. The integrated reflector had a measured gain of 37 dB at 119 μm. This makes the double-dipole antenna ideally suited as a feed for high resolution tracking or for long focal length casegrain antenna systems.**

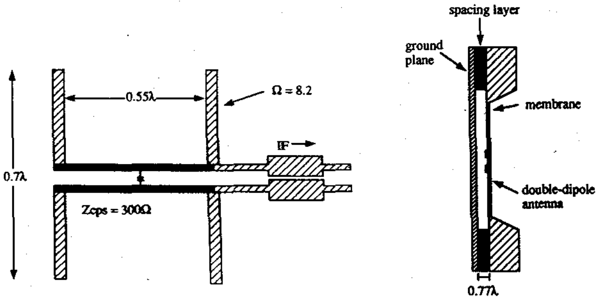

Fig. 1. Top view and side view of double-dipole antenna.

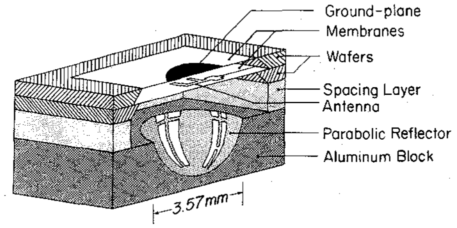

Fig. 2. Cut-view of reflector antenna with double-dipole and ground plane.

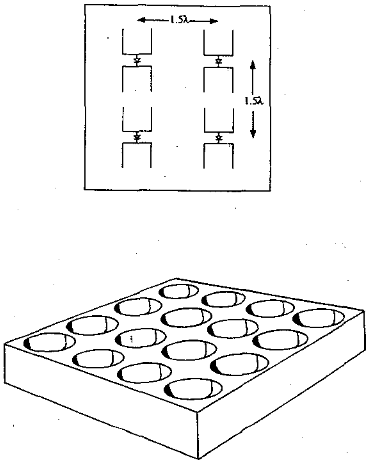

Fig. 3. Methods of arraying. Arraying the feed (top) and arraying the reflector (bottom).

I. Introduction

The USE of thin dielectric membranes for millimeter-wave integrated-circuit antennas is now a well established technique for high-efficiency designs [1], [2]. The membranes are very thin compared to a free-space wavelength and the antennas do not suffer from dielectric and substrate-mode losses. Recent measurements on integrated-horn and corner-reflector antennas [3], [4] show well behaved patterns and main-beam efficiencies greater than 85%. However, these antennas have differing *E* and *H*-plane patterns and a relatively high cross-polarization component (−16 dB) in the 45°-plane. They also require a controlled process of anisotropic etching of silicon or GaAs wafers. It is possible to integrate a radiating structure consisting of two dipole antennas on a dielectric membrane and backed by a ground plane that results in rotationally symmetric patterns and a very low cross-polarization component (Fig. 1). The double-dipole antenna is very simple to fabricate, resulting in similar directivities to the integrated-horn antenna, and has a high coupling efficiency to f/0.7-f/1 reflector systems.

For high resolution tracking, or for efficient coupling to long focal length antenna systems, a much higher gain antenna is needed. This can be readily accomplished by integrating a reflector with the double-dipole design (Fig. 2). The design is similar to the dielectrically filled parabola investigated by Siegel *et al.* [5]. However, it requires no dielectric and associated matching layer which are difficult to fabricate at submillimeter-wave frequencies. The design exhibits high coupling efficiency to Gaussian

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Manuscript received August 30, 1991; revised December 30, 1991. This work was supported by the NASA/Center for Space Terahertz Technology at the University of Michigan.

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IEEE Log Number 9106780.

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beams and can be easily arrayed for imaging systems applications. The imaging may be accomplished by fabricating multiple reflectors or by using multiple double-dipole antennas in the focal region of a single reflector (Fig. 3).

II. Double-Dipole Antenna

Double-dipole antennas have been previously investigated at millimeter-wave frequencies and have showed promise for high-efficiency applications [6]–[8]. The design consists of a double-dipole antenna integrated on a dielectric membrane and backed by a ground plane. The detector is integrated at the center of the coplanar stripline. A low-pass filter is used to isolate the IF/bias lines from the antenna. For far-field pattern calculations, the antenna current distribution is given by the standing-wave current on an open-circuited transmission line. The method of images is used to account for the ground plane [9]. The radiation pattern can be made rotationally symmetric by the choice of the antenna lengths (l), the antenna spacing (d) and the ground-plane distance from the membrane (h).

Two sets of double-dipole antennas with rotationally symmetric patterns were designed. Design #1 had parameters $l = 0.7\lambda$, $d = 0.55\lambda$, $h = 0.77\lambda$, Z (coplanar strip) $= 300\ \Omega$ (calculated from [10]) and a measured input impedance on a 2 GHz microwave model of a nearly constant 50 Ω for a ±5% bandwidth (Fig. 4). The calculated main-beam efficiency (to −20 dB) is 88%. The coupling efficiency to Gaussian beams is 84%, where Θ_0 is varied to maximize gaussicity (see Appendix). The design has a 10-dB beamwidth of 78° and a directivity of 11.7 dB. Design #2 included a short stub off the detector and had parameters $l = 0.9\lambda$, $d = 0.59\lambda$, $h = 0.73\lambda$, Z (coplanar strip) $= 200\ \Omega$ and a measured input impedance centered around $50 + j50\ \Omega$ for a ±5% bandwidth. The calculated main-beam efficiency of design #2 (to −20 dB) is 91% and the coupling-efficiency to Gaussian beams is 88%. This design has a 10-dB beamwidth of 70° and a directivity of 13.2 dB. Table I shows that the two designs maintain good efficiencies for at least a ±5% bandwidth. Both feed antennas can illuminate a reflector uniformly in phase and with a −10 dB to −20 dB taper depending on the size of the reflector. Also, both antenna designs yield impedances which are compatible with Schottky and SIS detectors at around 200–300 GHz. Therefore both designs are ideal as feeds for paraboloidal reflectors.

The measured electromagnetic coupling between two double-dipole antennas (for either design) in the H-plane was lower than −20 dB and −30 dB for a center-to-center spacing of 1λ and 1.5λ, respectively. The coupling in the E-plane was negligible for center-to-center spacing greater than 1.25λ. It is therefore possible to array the antennas for diffraction-limited imaging.

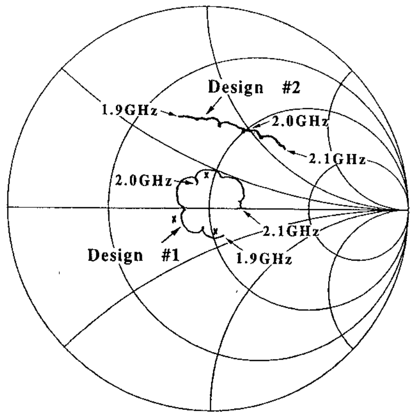

Fig. 4. Measured input impedance of feed with a 2 GHz model. The x's represent the theoretically predicted input impedances.

Design #1 was built for 246 GHz applications (Fig. 5). For measurement purposes, a bolometer was integrated at the center of the coplanar stripline. The bolometer impedance was 80 Ω with a responsivity of 10 V/W at a 100 mV bias. The pattern was measured at 234–258 GHz using 78–86 GHz Gunn sources, and a wideband (220–270 GHz) tripler. The Gunn sources were modulated at 300 Hz, and the output of the bolometer was fed to a PAR-124A lock-in amplifier. The signal-to-noise ratio was better than 20 dB.

The measured patterns agree very well with theory up to 45° (Fig. 6) where diffraction effects from the measurement set-up dominate. The theory predicts a sidelobe level lower than −13 dB in the E-plane at around 60 degrees and a −27 dB cross-polarization component in the 45°-plane at about 2 degrees. The sidelobe level could not be confirmed due to the measurement set-up, but a cross-polarization component less than −22 dB was measured at 30–35°. Pattern measurements at $0.95f_0$ (234 GHz) and $1.05f_0$ (258 GHz) agree well with theory and result in symmetric patterns (Fig. 7). The slight dip of 1 dB at normal incidence at 258 GHz is not predicted by theory and could not be explained.

III. Design of the Reflector Antenna

A. Theory

The far-field patterns of a parabolic reflector with a double-dipole feed are found by computing the Fourier integral of the fields in the aperture plane chosen to be the focal plane of the reflector [9], [11]. The reflector is assumed to be in the far field of the feed, and a ray optics approach is used to find the fields on the aperture. For a 30λ-diameter reflector illuminated by the double-dipole feed considered above, the 3 dB and 10 dB beamwidths are 4.4° and 8°, respectively, resulting in a 39 dB gain. The cross-polarization was also computed and found to be below −30 dB.

When the feed is displaced from the focus, as in the case of a focal plane imaging system, a search is needed to find the specular point for any given observation point

TABLE I
CHARACTERISTICS OF TWO DOUBLE-DIPOLE DESIGNS

ANTENNA #1: ($l = 0.7\lambda$, $d = 0.55\lambda$, $h = 0.77\lambda$, $Z_{cps} = 300\ \Omega$)

Freq.	Z_{ANT}	Gain	X-pol	ϵ_{mb} (−20 dB)	ϵ_{Gauss} ($\theta_0 = 30°$)	ϵ_{Gauss} ($\theta_0 = 27°$)
$0.90f_0$	~50 Ω	—	—	—	64.7%	66.5%
$0.95f_0$	~50 Ω	11.8 dB	−27 dB	82%	77.4%	77.1%
f_0	~50 Ω	11.7 dB	−26 dB	88%	83.4%	81.1%
$1.05f_0$	~50 Ω	11.2 dB	−25 dB	91%	84.8%	80.9%
$1.10f_0$	~50 Ω	—	—	—	82.7%	77.3%

ANTENNA #2: ($l = 0.9\lambda$, $d = 0.59\lambda$, $h = 0.73\lambda$, $Z_{cps} = 200\ \Omega$)

Freq.	Z_{ANT}	Gain	X-pol	ϵ_{mb} (−20 dB)	ϵ_{Gauss} ($\theta_0 = 27°$)	ϵ_{Gauss} ($\theta_0 = 24°$)
$0.90f_0$	—	—	—	—	66.5%	67.9%
$0.95f_0$	$30 + j25\ \Omega$	13.4 dB	−28 dB	85%	82.1%	80.9%
f_0	$50 + j50\ \Omega$	13.2 dB	−29 dB	91%	88.1%	84.9%
$1.05f_0$	$80 + j60\ \Omega$	12.8 dB	−30 dB	93%	88.7%	84.1%
$1.10f_0$	—	—	—	—	86.3%	80.9%

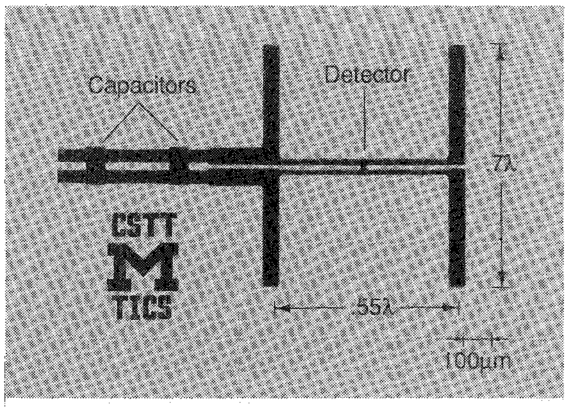

Fig. 5. Photograph of the double-dipole antenna for 246 GHz. The two rectangles to the left of the antenna are metal-insulator-metal capacitors for the IF-filter.

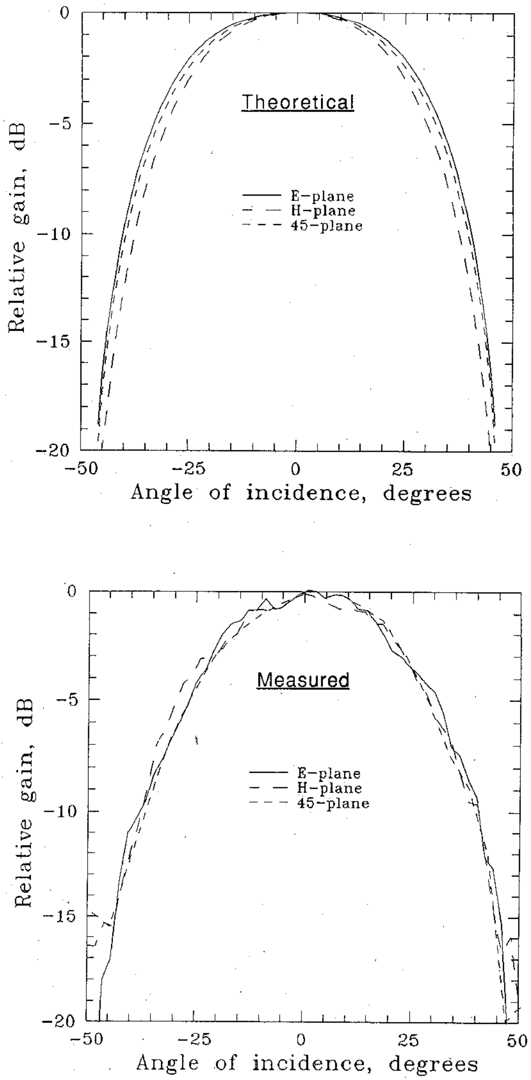

Fig. 6. Measured and theoretical double-dipole patterns at 246 GHz.

in the aperture plane (Fig. 8). The specular point must be found in order to determine the phase (since the phase is no longer uniform across the focal plane) and the amplitude (resulting from the angle the ray is emitted from the feed). One way to find the specular points is to use Fermat's principle of stationary optical path length. It is a particularly useful technique since it can be used with any arbitrary position of feed and any arbitrary surface [11]. For a given aperture point, the specular point is found by minimizing the optical path length. A good initial guess is to assume that the specular point is directly beneath the aperture point, since a small movement of the feed will create only a slight movement in the specular point. Fermat's principle is a well known variational expression and thus the program always converges. In fact, on average, six iterations were needed to converge to a sufficient accuracy in the far-field patterns. Fig. 9 shows the resulting *H*-plane patterns for a lateral displacement of the feed

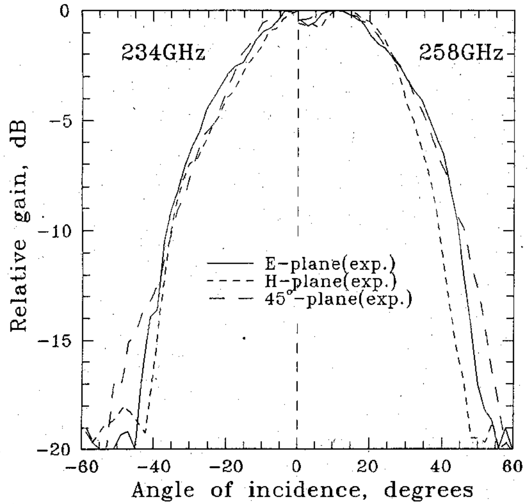

Fig. 7. Measured double-dipole patterns at 234 GHz and 258 GHz.

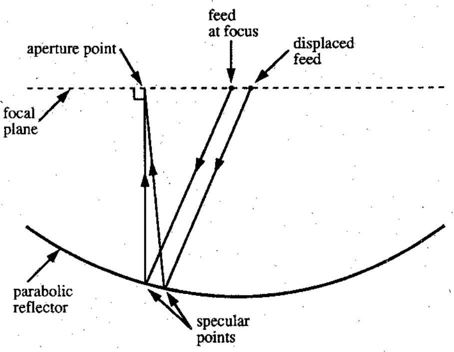

Fig. 8. A diagram of the ray-tracing method. Notice that for a feed displaced from the focus, the ray is not collimated.

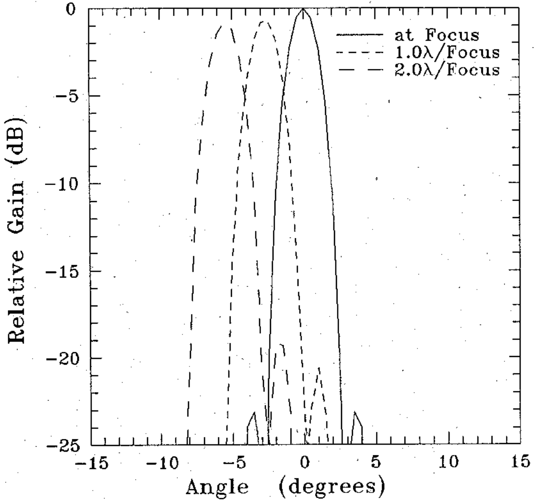

Fig. 9. Theoretical *H*-plane patterns for a displaced feed.

from the focus. One can see that for a one wavelength feed displacement, the main beam shifted by about 3 degrees. For a two wavelength displacement the beam shifted about 6 degrees, with the highest sidelobe still below −19 dB.

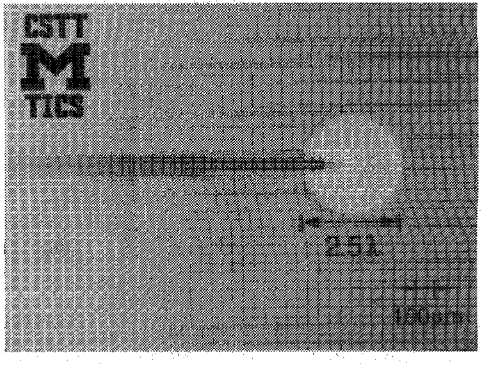

Fig. 10. Photograph of the double-dipole antenna suspended above a circular ground plane for 119 μm.

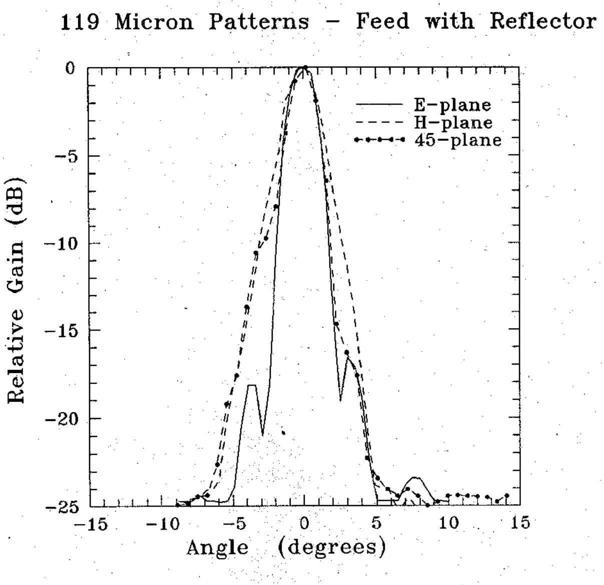

Fig. 11. Measured reflector patterns at 119 μm.

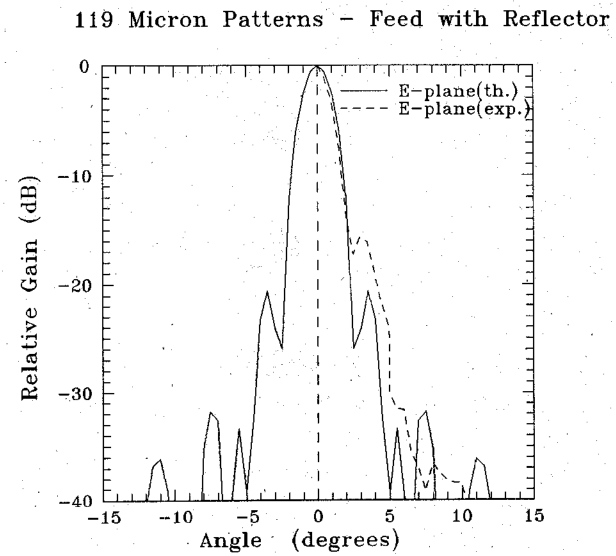

Fig. 12. Comparison of theoretical and measured *E*-plane reflector patterns at 119 μm.

B. Experiment

A double-dipole antenna with parameters of design #1 was built for a wavelength of 119 μm on a 1 μm-thin membrane with dimensions of 4 × 4 mm (Fig. 10). The ground-plane was built on a similar membrane and consisted of a circular patch of evaporated gold 1000 Å thick with a diameter of 2.5λ. The ground plane was aligned and attached to the antenna wafer using spacers made of silicon wafers polished to approximately 92 μm thickness. It was later realized that the spacers were too thick, and the resulting measured *H*-plane feed patterns were not optimal. Fortunately, the Fourier transform property of the reflector is forgiving and good reflector patterns were obtained. The double-dipole antenna and ground-plane are very small compared to the reflector's aperture, thus resulting in little loss due to aperture blockage. Also, the IF/bias lines are orthogonal to the polarization of the received wave resulting in minimal scattering loss.

In order to take the reflector patterns, the reflector was mounted on an *x-y-z*-tilt positioner and moved around until maximum power was received and symmetrical patterns were measured. The parabolic reflector was machined out of aluminum to a surface finish of around 120 Å and is 30λ (3.57 mm) in diameter. Fig. 11 shows the measured *E*, *H*, and 45°-plane patterns at 119 μm. The calculated gain from the measured data is 37 dB. Figure 12 shows the measured *E*-plane compared with theory. The theoretical pattern included the effect of aperture blockage from the 2.5λ ground plane. The disagreement below -15 dB is likely due to the improperly assembled feed structure. The *H*-plane pattern was wider than the design, and we believe that this is due to the *H*-plane feed pattern being narrower than expected. The measurements show that high-gain antenna patterns are easily obtainable at submillimeter frequencies. Measured patterns also confirmed the shift in the main lobe for a displaced feed, indicating the option of arraying the antennas for diffraction-limited imaging.

IV. CONCLUSION

A high-efficiency submillimeter-wave antenna has been presented. It is a double-dipole design backed by a ground plane which results in nearly equal *E*, *H* and 45°-plane patterns with a gain of 12–13 dB and an input impedance of around 50 Ω. A 246 GHz design showed very good agreement with the theoretical patterns and a measured cross-polarization level below -22 dB. The electromagnetic coupling between two sets of dipoles was below -20 dB (-30 dB) for 1λ (1.5λ) separation, thus allowing the antenna to be arrayed for diffraction-limited imaging. Measured patterns with the double-dipole antenna illuminating a parabolic reflector at 119 μm confirmed the theoretically predicted reflector *E*-plane patterns to -15 dB, in spite of the double-dipoles being poorly aligned to their ground-plane. The double-dipole antenna is a simple antenna for submillimeter-wave tracking and imaging applications.

APPENDIX

The field representation of a Gaussian beam is of the form: $\boldsymbol{E}_{\text{Gauss}}(\theta) = \hat{\epsilon}\,\exp^{-[\theta/\theta_0]^2}$. The coupling efficiency between an antenna pattern and a Gaussian beam is calculated using the formula [12], [13]:

$$\eta_{\text{Gauss}} = \frac{\left| \iint [\hat{\epsilon}_{co} \cdot \boldsymbol{F}(\theta, \phi)] \exp^{-(\theta/\theta_0)^2} \sin\theta \, d\theta \, d\phi \right|^2}{\iint |\boldsymbol{F}(\theta, \phi)|^2 \sin\theta \, d\theta \, d\phi \iint \exp^{-2(\theta/\theta_0)^2} \sin\theta \, d\theta \, d\phi}$$

where $\boldsymbol{F}(\theta, \phi)$ is the far-field pattern of the antenna, and $\hat{\epsilon}_{co}$ is the co-pol unit vector. The value Θ_0 is varied to maximize the coupling efficiency.

ACKNOWLEDGMENT

The authors would like to thank Dr. Gordon Chin and Dr. Hemant Davée of NASA/Goddard for allowing us to use their 119 μm laser source.

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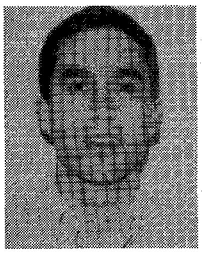

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Gabriel M. Rebeiz (S'86–M'88), for a photograph and biography, see this issue, p. 794.