

# Broad-Band Characterization of Millimeter-Wave Log-Periodic Antennas by Photoconductive Sampling

Mark M. Gitin, Frank W. Wise, *Member, IEEE*, G. Arjavalingam, *Senior Member, IEEE*, Y. Pastol and Richard C. Compton, *Member, IEEE*

**Abstract**—Results of photoconductive sampling measurements used to characterize millimeter-wave log-periodic antennas with continuous, simultaneous frequency coverage from 10 to 300 GHz are presented. Polarization properties are investigated employing wire-grid polarizers. This study reveals new information on structure resonances and antenna polarization.

## I. INTRODUCTION

THE LOG-PERIODIC antenna is a member of a class of broadband antenna structures called frequency independent antennas, which also includes the bow-tie [1] and equiangular spiral antenna [2]. An antenna will be frequency independent if its dimensions when measured in wavelengths remain constant for all frequencies. An infinite bow, which is defined entirely by angles, would exhibit these properties [1]. However, truncating its length degrades its frequency independence since currents are reflected from the antenna ends. The log-periodic antenna is a modified bow with notches and teeth to force the currents to change direction, and radiate before reaching the antenna ends. The planar log-periodic, first investigated from 0.4 to 5 GHz in a sheet metal design by DuHamel [3], [4], is now being considered for millimeter-wave applications. While the early low frequency designs were fabricated on an unsupported metal sheet, monolithic millimeter-wave applications often require a supporting substrate with a high dielectric constant such as GaAs ( $\epsilon_r \approx 12$ ). This dielectric substrate has a dramatic effect on the current distribution and the resulting antenna pattern [5]. Integrated log-periodic antenna structures have demonstrated wideband performance and have been incorporated into millimeter-wave systems, most recently in a 30–180 GHz harmonic mixer-receiver [6]. Single frequency antenna pattern measurements for the planar log-periodic antenna have been made at 94 GHz [7] and 180 GHz [6]. These frequency domain techniques measure received power relative to a transmitted signal at a single frequency. Complete, continuous millimeter-wave characterization of the log-periodic antenna with these methods would require many measurements and several different sources, and therefore has not been attempted. Photoconductive sampling, however, is a high-speed opto-electronic time

domain technique which provides broad continuous frequency characterization in a single experiment. This method uses an ultrafast laser and pump-probe techniques to measure with sub-picosecond resolution, which translates to hundreds of GHz of measurement bandwidth. Variations on the technique described here have been used by other researchers for the broad-band characterization of the equiangular spiral [8] and another log periodic structure, the wire log spiral [9]. In this work, log-periodic antennas were integrated with sub-picosecond photoconductive switches to obtain a time domain measurement of the antenna. Antenna polarization was also investigated with a wire grid polarizer.

## II. ANTENNA STRUCTURE AND EXPERIMENTAL SETUP

The structure shown in Fig. 1 is a planar log-periodic antenna with the  $n$ th tooth characterized by an inner radius  $r_n$  and an outer radius  $R_n$  where  $R_n/r_n = \sqrt{2}$  and  $R_{n+1}/R_n = 2$ , and angles  $\alpha = 135^\circ$  and  $\beta = 45^\circ$ . The antennas were fabricated on silicon-on-sapphire (SOS) substrates ( $\epsilon_r \approx 10$ ) with 8 teeth, with the largest radius  $R_1$  of 1250  $\mu\text{m}$  and the smallest radius  $r_8$  of 5  $\mu\text{m}$ . The antenna is resonant when arc lengths ( $l_n$ ) are equal to  $\lambda_g/2$  where

$$l_n = \frac{\pi}{2} \bar{R} \text{ with } \bar{R} = \frac{R_n + r_n}{2} \text{ and } \lambda_g = \frac{\lambda_o}{\sqrt{\epsilon_{\text{eff}}}}$$

The corresponding resonant frequencies are

$$f_n = \frac{2c}{\pi(R_n + r_n)\sqrt{\epsilon_{\text{eff}}}} \text{ with } \epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2}$$

The longest and shortest teeth correspond to a theoretical design frequency coverage from 38 GHz to 6.7 THz. The antennas are photolithographically patterned on 432  $\mu\text{m}$  thick (SOS) wafers. A 10  $\mu\text{m}$  gap in the center of the antenna provides the photoconductive switch. The carrier lifetime in the 0.5  $\mu\text{m}$ -thick silicon epilayer is reduced to less than 1 ps by ion implantation [10]. The resulting switch has a sub-picosecond response. This response was determined with electrical autocorrelation measurements made on coplanar strip transmission lines fabricated on an SOS substrate with an implantation dose identical to that of the antenna [11]. A sampling gate of less than 1 ps corresponds to at least 300 GHz of measurement bandwidth. With similarly processed SOS sampling gates, frequencies greater than 300 GHz have been detected [12]. The technique of photoconductive sampling has

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M. Gitin and R. C. Compton are with the School of Electrical Engineering, Cornell University, Ithaca, NY 14853.

F. Wise is with the School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853.

G. Arjavalingam is with the IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598.

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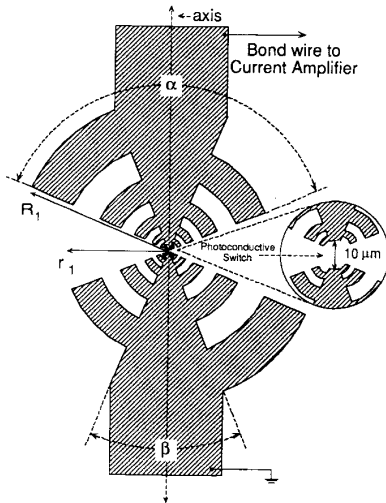


Fig. 1. Planar log-periodic antenna with  $R_n/r_n = \sqrt{2}$  and  $\alpha = 135^\circ$  and  $\beta = 45^\circ$  fabricated on implanted silicon-on-sapphire and integrated with a  $10 \mu\text{m}$  photoconductive switch.

been reviewed in [13] and so details of the method will not be presented here.

The antenna measurement system is shown in Fig. 2. Antennas on high dielectric constant substrates radiate most of their energy into the dielectric [5], [7]. The emitted radiation suffers refraction and total internal reflection at the sapphire-air interface. To minimize these effects, the antennas are mounted in the center of 3.5 in diameter alumina hemispherical lenses, with the substrate side glued to the flat surface of the hemisphere (see Fig. 2). These millimeter-wave lenses eliminate the refraction and total internal reflection by providing near normal incidence for radiation angles of interest. The lenses are chosen to be large enough so that the curved surface is in the far field at the lowest frequencies of interest, and so that reflections from the alumina-air interface will be outside the time window of interest. Alumina was chosen for the lens material to minimize reflections since it has a relatively isotropic dielectric constant which closely matches that of the sapphire substrates and has low dispersion and low loss for these frequencies [14]. The lenses were fabricated by precision splitting of a high-purity alumina sphere [15]. Connections to the antennas are made with bond wires to metal pads attached to the back side of the hemispherical lenses. Low frequency coaxial cables carry signals from the metal pads to the lock-in amplifier.

The laser system developed for this work is a mode-locked Titanium-Doped Sapphire laser producing 120 fs pulses at a 100 MHz repetition rate with up to 950 mW of average power at 780 nm. The laser design is a 4 mirror cavity containing a 1 cm sapphire rod doped with 0.1% Titanium, 2 SF-14 prisms for dispersion compensation, and an adjustable intracavity slit to facilitate slit-assisted self-mode locking and tuning. The laser is longitudinally pumped by 4 to 7.5 Watts from a CW argon ion laser operating on all blue-green lines. (This mode-locked laser is similar in performance and operation to that

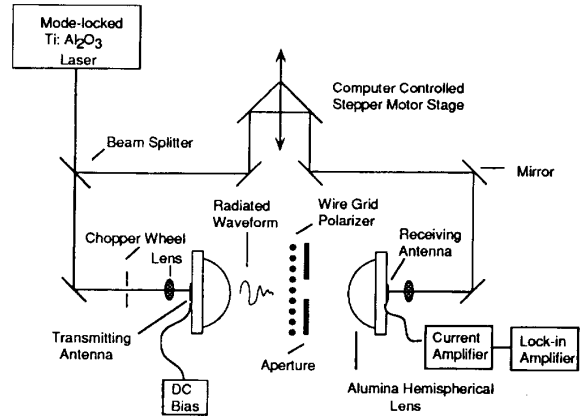


Fig. 2. Pump-probe measurement system for photoconductive sampling of broadband millimeter wave antenna structures. An important feature of the pump-probe technique is that RF signals are effectively isolated from the current amplifier and other DC circuitry due to the radiation resistance of the antenna and the large inductance of the connecting wires.

described in [16]). The optical pulse train is attenuated and split into an excitation and probe beam. A computer-controlled stepper motor stage in the probe beam's path provides a variable time delay between the pulses. An average power of 50 mW is focused into each antenna's central gap, exciting a free carrier density of approximately  $2 \times 10^{19}/\text{cm}^3$ .

Alignment is a critical issue for both the optical and millimeter wave beams. Millimeter wave beam alignment is facilitated by the choice of anti-collinear pump and probe optical beams. The optical beams can be accurately aligned with the use of an infra-red viewer, and the antennas are carefully centered in the optical beams. Retroreflected optical beams ensure that the antennas are normal to the optical beams and parallel to one another. Final optical beam alignment into the  $10 \mu\text{m}$  photoconducting gaps is completed by fine positioning of the 10 mm focal length lenses. The optimum alignment is ensured by maximizing the DC photocurrents. The hemispherical lenses are spaced 20 cm apart giving an equivalent air spacing between the antennas of 48 cm. This spacing ensures that the receiver is well into the far-field for frequencies above about 5 GHz. Several other spacings were used to check that the measured waveform was independent of antenna separation. The system is designed with a time window which includes 300 ps of radiated waveform without reflections. This ability to gate the appropriate portion of the time domain waveform eliminates the need for a reflectionless chamber. A  $12 \times 12$  inch absorbing wall with a 2.5 cm aperture is centered between the hemispherical lenses to filter low frequency signals due to radiation from bond wires and coaxial connections to the antennas. A free-standing wire grid polarizer is placed between the antennas to separate co- and cross-polarization responses. The polarizer is fabricated with  $36 \mu\text{m}$  wires with a center-to-center spacing of  $100 \mu\text{m}$ . Therefore, for frequencies below 500 GHz, the polarizer has greater than 95 percent transmission for radiation with the electric field polarized perpendicular to the wires, and less

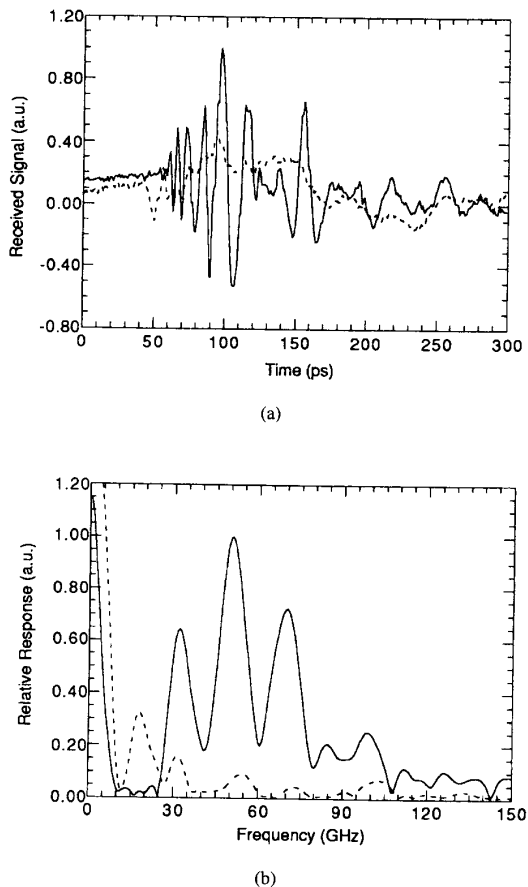


Fig. 3. Polarization decomposition displaying. (a) Electric field co- and cross-polarization of planar log-periodic antenna as measured by photoconductive sampling. A wire grid polarizer was used to separate the two polarizations and an aperture was used to filter out low frequency bias line radiation. The solid line is co-polarization and the dotted line is cross-polarization. (b) Fast Fourier Transform (using Hanning window function) of photoconductive sampling data from figure (a) for electric field co- and cross-polarizations.

than 5 percent transmission for radiation with the electric field polarized parallel to the wires [17]. The transmitting antenna is DC biased with 9 volts and the receiving antenna is fed directly into a current (transimpedance) amplifier with a gain of  $10^8$  V/A and then into a lock-in amplifier. Typical output signal levels on the lock-in amplifier of 10–50 millivolts correspond to currents of 100 to 500 pA. A micro-computer controls the optical delay and collects the data from the lock-in amplifier.

### III. RESULTS

Measurements of the antennas oriented with  $\theta = 0^\circ$ , where we define  $\theta$  to be the rotation of the receiving antenna relative to the transmitting antenna are shown in Fig. 3(a). The co-polarization is measured with the polarizer oriented with the wires parallel to the antenna axis (polarization perpendicular to the axis), and the cross-polarization is measured with the polarizer rotated by  $90^\circ$ . The lock-in amplifier time constant was set for 300 ms, with the total time for a 300 point scan of about 8 minutes. The pulse is generated with the

photoconductive switch in the center of the antenna, and as the energy flows out on the antenna, the shorter teeth are resonant first in time followed by the longer teeth. Therefore, the waveform contains a distinctive frequency chirp consistent with [8] for the log spiral antenna, and [9] for the wire log periodic antenna. A Fast Fourier Transform is performed with a Hanning window function [18] applied to the data, and the frequency spectrum is shown in Fig. 3(b). The peak at DC in the Fourier Transform is a result of the time window not capturing the residual energy beyond 300 ps. With a longer time window, the Fourier Transform would go to zero at zero frequency. The spectrum is displayed to 150 GHz since less than 2 percent of the energy is contained beyond this frequency. The co-polarization frequency spectrum contains resonances which have not been previously observed for this structure. The peaks are spaced at intervals close to that of the antenna teeth which nearly coincide with  $R_n/r_n = \sqrt{2}$ . This appears to show that the antenna has clear structural resonances with less gain at the non-resonant frequencies. This large swing in antenna gain suggests that the antenna is not frequency independent and is therefore not well impedance matched at the non-resonant frequencies. These resonances are an important consideration for efficient millimeter-wave system design. The peak in the cross-polarization at 15 GHz is due to a  $\lambda/2$  resonance with the total antenna length. The ratio of co-polarization to cross polarization agrees well with previous measurements at single frequencies [6], [7].

To examine the polarization properties of the antennas, measurements were made for two angles of  $\theta$ . For a linearly polarized antenna polarized along single teeth, a change in the magnitude of the frequency spectrum would be expected as a function of the relative antenna angle, with the difference being greatest for  $\theta = +45^\circ$  and  $\theta = -45^\circ$ . Figs. 4(a) and 4(b) display the time and frequency domain waveforms for these values of  $\theta$ . Measurements for each angle of  $\theta$  require a new alignment. Since measured amplitudes are alignment sensitive, the curves in Fig. 4 are normalized to unity. The frequency domain data shows that the relative magnitudes of the frequency components are almost identical, while the time domain plot shows nearly a  $180^\circ$  phase shift for the first half of the waveform. The frequency domain plot suggests that the currents are not only linearly polarized along single teeth, but that the antenna is also resonant along broad arcs which include significant current contributions from adjacent teeth [19]. This is illustrated in Fig. 5. The  $\lambda/2$  resonant frequency  $f_{r2}$  of a single tooth is only a few percent different than the  $\lambda/2$  resonant frequency  $f_{r1}$  of a broad arc containing adjacent teeth. Therefore, a single resonant peak in the frequency domain plots of Figs. 3(b) and 4(b) may contain contributions from both resonant structures.

### IV. CONCLUSION

Photoconductive sampling was used to characterize the planar log-periodic antenna with continuous frequency coverage from 10–300 GHz. Results demonstrate that this antenna is not “frequency independent”, but instead displays resonances corresponding to physical lengths of the antenna of  $\lambda/2$ .

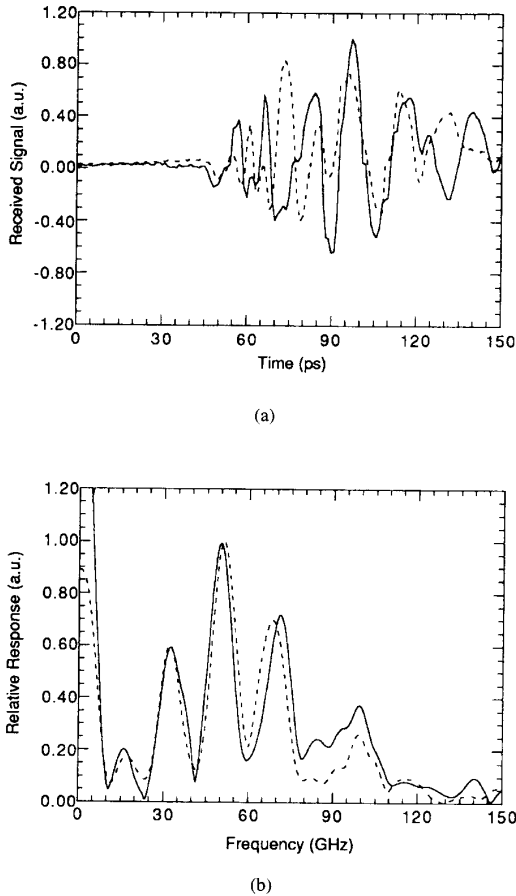


Fig. 4. (a) Measured electric field from log-periodic antennas for two angles of  $\theta$  between the transmitting and receiving antennas. Solid line is measurement with  $\theta = +45^\circ$  and dotted line is with  $\theta = -45^\circ$ . A near 180 degree phase shift is observed for the two angles. (b) Fast Fourier Transform (using Hanning window function) of measured electric field as a function of the relative rotation angle  $\theta$  from (a). The solid line is for  $\theta = +45^\circ$  and the dotted line is for  $\theta = -45^\circ$ . Little change is seen in the relative magnitudes of the frequency components for the 2 angles, suggesting that the currents may not only be resonant on single teeth.

These results are important for millimeter-wave system design since use of these antennas over a broad frequency range will result in inefficient operation at strongly non-resonant frequencies. A wire grid polarizer was incorporated into the measurement system to separate co- and cross-polarizations. The ratio of co- to cross-polarization agrees well with previous measurements at single frequencies. A resonance in the cross polarization frequency spectrum at 15 GHz is also revealed. This peak corresponds to the half wave resonance of the total antenna length. Measurements of the antennas as a function of the relative angle of rotation  $\theta$  between  $+45^\circ$  and  $-45^\circ$  show little change in the relative magnitudes of the frequency components. This measurement suggests that the radiation is not just linearly polarized along single teeth, but that the resonances are also along broad arcs with significant current contributions from adjacent teeth. A phase shift with rotation is also noted in the time domain data.

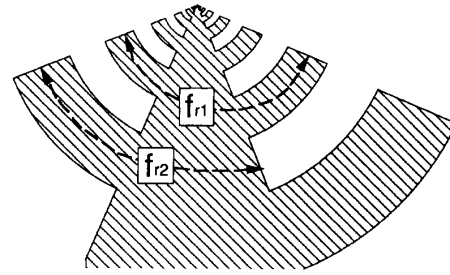


Fig. 5. The  $\lambda/2$  resonant lengths corresponding to the broad arc containing  $f_{r1}$  and the single tooth containing  $f_{r2}$  differ by only a few percent. Therefore, a single measured resonance in the frequency domain may contain contributions from both structures. The cross-polarization serves as a rough measure of the relative coupling to the two resonances.

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**Mark M. Gitin** was born in Los Angeles, CA, in June, 1966. He attended the University of California, Davis, where he received the B.Sc. degree in electrical engineering in 1988. In 1989, he obtained the Master of Engineering degree in electrical engineering from Cornell University and continued on to receive the Ph.D. degree from Cornell in 1993. His doctoral research was on ultrashort-pulse lasers and their application to the characterization of millimeter-wave devices and antennas. Mark is currently with Coherent, Inc., where he is a member of Coherent Laser Group, Santa Clara, CA.

**Frank Wise** (S'87-M'88) received the B.S. degree in engineering physics from Princeton University, Princeton, NJ, in 1980 and the M.S.E.E. degree from the University of California, Berkeley, in 1981. During 1982 and 1983 he was a member of the Advanced VLSI Development Laboratory at Bell Laboratories, Murray Hill, NJ. From 1984 to 1989 he was a graduate student at Cornell University. Since 1989, he has been a faculty member of the Department of Applied Physics at Cornell University.



**G. Arjavalngam** (S'80-M'83-SM'90) was born in Colombo, Sri Lanka, in March 1957. He obtained the B.A. degree from Cambridge University, U.K., in 1978, and the M.S. and Ph.D. degrees from the University of California, Berkeley, in 1980 and 1983, respectively, all in electrical engineering. His doctoral work was on the production of ultrashort light pulses with mode-locked lasers. Since 1983, he has been at the IBM Thomas Watson Research Center, where he has worked on the amplification of ultraviolet subpicosecond pulses and various applications of short pulse technology. His most recent work involves the electrical characterization of computer interconnect structures and the materials used to fabricate them. Currently, he is Manager of Package Design, Analysis, and Measurements at the T. J. Watson Research Center. He has published over 50 papers and has co-chaired the IEEE Topical Meetings on Optical-Microwave Interactions, and Package Engineering. He is a Senior Member of the IEEE and a member of the Optical Society of America.



**Yvon Pastol** was born in Lannion, France, on June 27, 1961. He received the Engineer degree from the Institut Supérieur d'Electronique de Paris in 1983, and the Ph.D. in solid-state physics from the University of Paris in 1987. He then joined the IBM Research Division as a postdoctoral fellow at the Thomas J. Watson Research Center, Yorktown Heights, NY, where he worked on the development of spectroscopy techniques with IBM-France, Corbeil-Essonnes, France.



**Richard Compton** (S'84-M'87) is an Assistant Professor in the School of Electrical Engineering, at Cornell University. He completed his B.Sc. at the University of Sydney in 1982. Before starting his Ph.D., he developed, fabricated, and tested components for submillimeter wave lasers for the Commonwealth Scientific and Industrial Research Organization. During his Ph.D. studies at the California Institute of Technology (1983-1987), he worked as a Fulbright scholar on several projects, including the design, fabrication, and measurement of millimeter and submillimeter-wave antennas and arrays. Mr. Compton co-developed an interactive microwave CAD education package, *Puff*, which is used in microwave classes at universities worldwide. Over 10,000 copies of *Puff* have been distributed. At Cornell University his group specializes in millimeter-wave integrated arrays and has contributed pioneering work in the area of quasi-optical power combining. He has been a consultant for the Hughes Aircraft Company and TRW, and is currently a National Science Foundation Presidential Young Investigator.