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Photonic-Assisted Reactive-Near-Field Analysis of a 3 dB-Tapered Ka-Band Array Antenna

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Abstract

A Ka-band microstrip array antenna for wide-range detection of moving targets is analyzed through a photonic-assisted reactive-near-field characterization technique. The antenna array employs a 3-dB-tapered feed network to suppress the sidelobe level while retaining a wide azimuth beamwidth for a wide detection range. The relative near-electric field patterns of the array and its 3-dB-tapered feed lines have been measured using an electro-optic field-mapping technique for minimally invasive millimeter-wave sensing. A number of typical limitations on the technique, involving bandwidth, low signal-modulation depth, and high laser-induced noise in high-frequency applications, have been overcome by suppressing the carrier portion of the optical interrogation beam.

Key words : Detection of Moving Target, Microstrip Array Antenna, Electro-Optic Sensing, Near-Field Measurement.

Ⅰ. Introduction

For the design and analysis of millimeter-wave antennas and microwave circuits, a complete characterization of the near-electric-field distribution and polarization can provide a wide variety of unique and valuable information. Such near-electric vector fields can be measured by the electro-optic sensing/sampling(EOS) technique, which is widely known as a minimally invasive diagnostic tool for microwave sensing and imaging[1].

EOS measurement techniques typically possess an extremely broad frequency response, including coverage of the entire microwave range and even part of the terahertz regime. This is due to the properties of electro-optic(EO) crystals and short-pulse lasers[2]. However, for radio frequency(RF) sensing up to the millimeter-wave range, the use of pulsed lasers may be found to be prohibitively expensive, while direct sensing of the RF components becomes technically challenging due to the need for a high-bandwidth detector and read-out instrument. To address these issues, mixing techniques are commonly employed to down-convert the RF band to a subsonic intermediate frequency(IF) that results from the frequency beating between two modulation light sidebands of a continuous-wave(CW) optical carrier at the signal and local-oscillator(LO) frequencies[3]~[5].

Typically, EO sensing with a cw-laser beam suffers from bandwidth limitations, low signal-modulation depth, and high laser-induced noise for millimeter-wave sensing applications. To overcome these issues, a multi-stage carrier suppression technique was used for enhancing the EO signal portion of the optical interrogation beam. The three cascaded carrier suppression stages of the EO measurement system, located within an electro-optic modulator used to generate a local-oscillator signal as well as within the electro-optic sensor itself, were used to successfully perform near-field sensing on a full Ka-band antenna array, including its phase impedance-matching network.

Ⅱ. Design of a Ka-Band Receiver Array Antenna with 3-dB-Tapered Network

We analyze a microstrip array antenna designed to operate at 35.5 GHz as a position detector of moving targets. The array was designed to have a relatively narrow beamwidth in the elevation plane for a wide detection range, compared to the beamwidth in the azimuthal plane. This was achieved by aligning the electric-field plane of each element to the array axis. Employing a 3-dB-tapered serial-parallel feed network[6], the array had a sidelobe level of less than -20 dB, while retai-

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ning a wide azimuthal beamwidth[7].

As illustrated in Fig. 1, the 3-dB-tapered feeding structure causes the feeding power to degrade by half after passing each element; thus, the feeder is designed to deliver 1/2, 1/4, 1/8, and 1/16 of the feeding power to each sub-array antenna relative to the center. In general, the phase difference between elements can be eliminated by making the distance between elements λ_0. In this array set, rather than narrowing the element spacing to less than λ_0 to minimize the antenna size, the feeding lines for the 12 sub-arrays(shown in Fig. 2) were meandered to compensate their phase differences accordingly.

The fabricated antenna layout is presented in Fig. 2, and the overall size of one-half of the array set(of an 8×2 receiver antenna) was reduced to 46×15.4 mm^2. Additional details of the design, specification, and analysis of the antennas with this 3-dB-tapered feed can be found in Ref. [7].

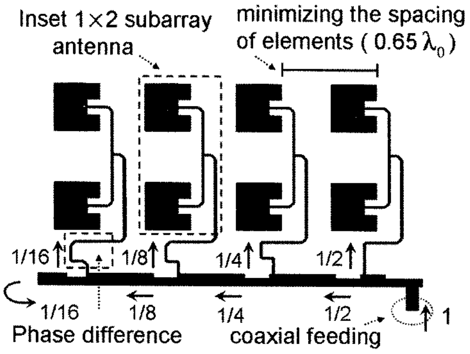

Fig. 1. Half of an 8×2 series-parallel receiving antenna with a 3-dB-tapered configuration feed network and power distribution scheme.

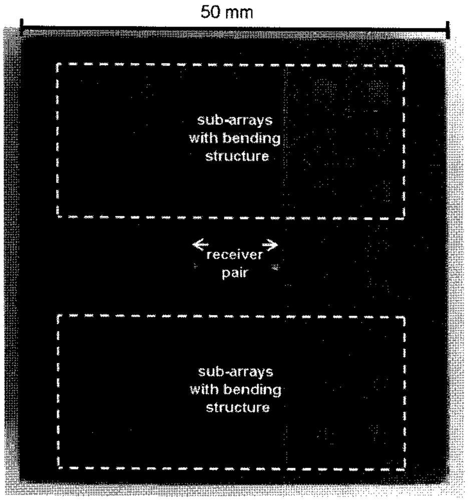

Fig. 2. A pair of 8×2 receiver antennas with a 3-dB-tapered feeding network.

III. Millimeter-wave Near-field Sensing with Multi-stage Optical Carrier Suppression

The characteristics of the antenna, including its feed structure, were analyzed by exploring the reactive-near-field radiation performance through a high-frequency EO sensing system. The use of a multi-stage optical carrier suppression technique, which enhanced the signal-modulation depth for both LO generation and EO sensing in millimeter-wave field measurements, will subsequently be described. This carrier suppression method enhances both the sensitivity and bandwidth of the photonic measurements, and it is useful even up to the Ka-band region for EO sensing techniques that use a continuous-wave laser beam.

The LO, amplitude-modulated light components are produced using an electro-optic modulator(EOM), and the frequency response of the EOM then determines the bandwidth of the LO modulation. Since the LO band must be close to that of the RF signal to create a reasonably low IF, it is crucial that the EOM bandwidth extends to the frequency of the RF signal. To avoid the expense of applying a millimeter-wave EOM to the generation of a millimeter-wave LO sideband, a commercial telecom-grade, X- or Ku-band modulator could be used instead, but only if its bandwidth and modulation depth could be enhanced. This is mainly because the modulation sidebands diminish for the higher frequencies, whereas the carrier component is maintained. To avoid a decrease in the modulation sidebands and the contrast of these sidebands with the carrier(i.e., the modulation depth), one may attempt to suppress only the carrier portion of the light beam.

To extend the bandwidth of EO sensing with a cw laser diode up to the millimeter-wave regime, a photonic down-mixing format previously used for X-[5] and K-band sensing[8] has been adopted. Two principal EO sections were employed in the probing system: an EOM to provide an intense amplitude modulation on the cw beam for the creation of the LO optical components, and the EO probe, which was used in concert with a photodetector to down-mix the LO and the RF signal. The minute, down-converted IF components contain amplitude and phase information proportional to that of the high-frequency RF signal. Although the EO sensitivity decreases for measurements at higher frequencies due to the degradation of modulation depth, this can be contained reasonably well by suppressing the carrier components.

3-1 First-stage Carrier Suppression

Operating an EOM at the minimum-transmission dc-

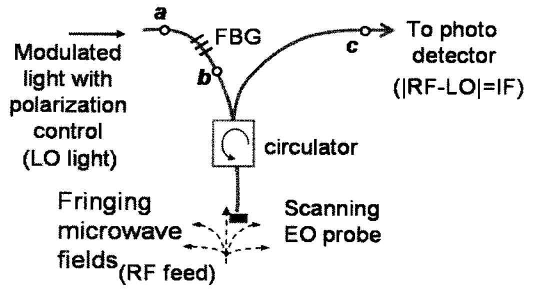

Fig. 3. Optical fiber-based heterodyne electro-optic sensing concept. Points *a*, *b* and *c* are the locations of the three carrier suppression stages(The whole system, including the detailed sensor structure, can be referred to in Ref. [5]).

bias point of its sine-squared modulation curve is a well-known technique for suppressing a carrier signal. Here, the ac part of the driving signal, which normally provides the LO for the photonic down-mixing, yields a predominant amplitude-modulated transmission at the second-order harmonic of the driving frequency, with a carrier that is significantly suppressed[8]. The suppressed carrier appreciably enhances the modulation depth, while the second-order harmonic of the driving frequency creates a doubled LO frequency sideband for down-mixing.

Although this harmonic sideband generation scheme produces a nonlinear output, the second-order component is dominant and actually serves as an efficient down-mixing source for enhanced frequency sensing without signal distortion. The antenna is fed at its resonant frequency of f_{RF}=35.5 GHz with +5-dBm input power. The solid-line spectrum shown in Fig. 4 represents the carrier-suppressed double sidebands when the EOM is driven with +11 dBm at 17.2985 GHz, a frequency that is LO/2(i.e., f_{LO}=35.497 GHz) compared to the second-order harmonic EOM output.

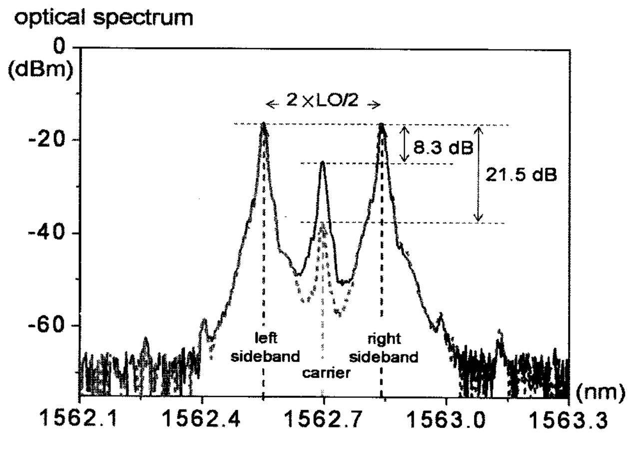

Fig. 4. Carrier-suppressed LO spectra at stages *a*(solid plot) and *b*(dashed gray plot) of Fig. 3(All signals attenuated by 20 dB).

3-2 Second-stage Carrier Suppression

Since the bandwidth and modulation-depth-enhancement technique relies on the nonlinearity of an EOM, a larger LO/2 input will yield a more efficient second-order LO harmonic. However, the damage threshold of the EOM and deficiencies of the drivers at higher frequencies will limit the modulation sideband of the second-order harmonic. The modulation depth, though, is determined by the carrier-to-sideband ratio, and thus the modulation efficiency can be further enhanced by additional carrier suppression.

The modulated input spectrum(Fig. 4) at stage *a* of Fig. 3 shows a carrier-suppressed double-sideband(DSB) with the second-order LO harmonic sidebands. A higher-frequency LO modulation yields a wider sideband separation, albeit with reduced amplitude. However, the wider sideband separation makes it easier to eliminate detrimental carrier components through filtering. For instance, the spacing between LO sidebands for the Ka-band signal is 0.29 nm as shown in Fig. 4. A fiber Bragg grating(FBG) filter of 0.2-nm full width at half maximum(FWHM) bandwidth accomplishes 13.2 dB of additional carrier suppression at stage *b*, as shown in Fig. 4, and thus the carrier-suppressed DSB spectrum essentially evolves into a single-sideband(SSB) case.

3-3 Third-stage Carrier Suppression

The prior two stages of carrier suppression enhanced the modulation depth of the LO sidebands that are used for mixing with the RF fields to be measured. The sensor itself yields an EO phase retardation when the signal RF electric field and the optical beam interact (i.e., the EO effect) within the probe crystal. Typically, the phase modulation is transformed into a minute amplitude modulation using the slope at the 50 % transmission point of the sine-squared amplitude-modulation slope for the EO sensor. However, there have been reports that the modulation depth can be enhanced by lowering the transmission along the sine-squared function to less than 50 %[9],[10].

It has been shown that an EO probe fabricated as a micro-cavity optical resonator offers a steeper intrinsic modulation slope without requiring conventional polarization optics to create the sine-squared modulation function[5]. The resonator-based modulation slope has more advantages than that of the conventional case, as it has its steepest slope around the minimum transmission regime. The resonant EO-fiber probe used herein is a 52-μm-thick x-cut $LiTaO_3$ wafer tip, which is coated so that it becomes a balanced resonator with $r \sim 0.81$ for the Fresnel field-reflection coefficient. As illustrated in Fig. 5, operating the LO sidebands around the steepest slope of the resonator curve yields a more efficient secondary RF modulation with less carrier power(*i.e.*, average transmission) than the conventional 50 % case.

Owing to the steep slope, both the left(red) and right (blue) LO sidebands yield different transmission(or reflection) optical outputs. Although this slope difference causes a different modulation depth and signal level, the same slope polarity(i.e., ascending in this case) allows the output modulation components to combine constructively in one common fiber path to the photodetector. The experimental spectrum of the left and right sidebands is shown in Fig. 6.

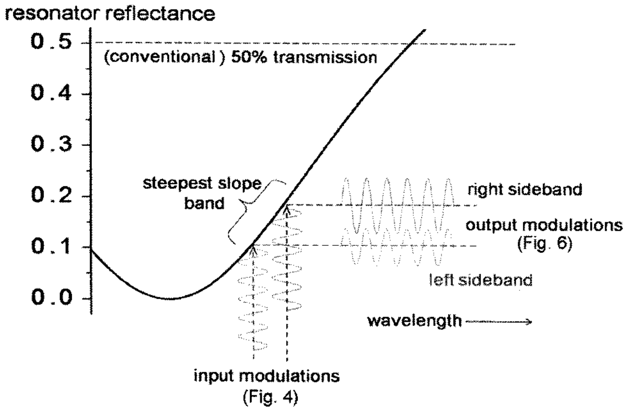

Fig. 5. Principle of carrier-suppressed electro-optic modulation for single-sideband optical input. The carrier is much stronger at the conventional 50 % transmission point, while the slope and sidebands are lower.

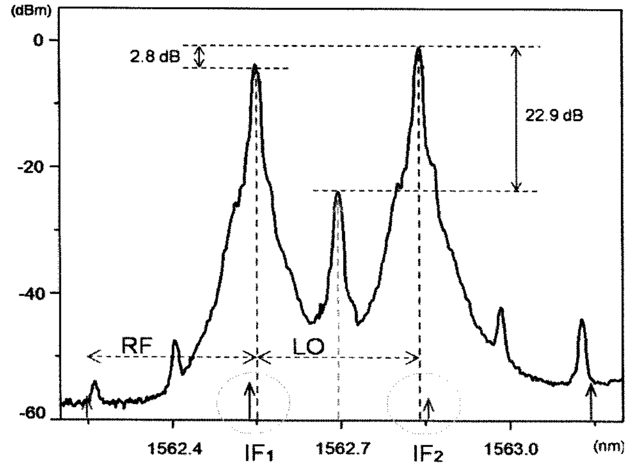

Fig. 6. Electro-optic-modulated LO and RF spectrum at stage *c* of Fig. 3(f_{LO}: 35.497 GHz, f_{RF}: 35.5 GHz, and f_{IF}: 1,2: 3 MHz).

Ⅳ. Millimeter-wave Near-Field Sensing of a Ka-Band Antenna

The two sideband spectra provided by the EO probe sensor contain minute levels of the RF sideband components. The two dominant beating regions(within the circles in Fig. 6) of the millimeter-wave-scale difference frequency of |LO-RF| yield sub-sonic IF components at a frequency of 3 MHz. The overall IF is a constructive summation of IF_1 and IF_2. The 35.497 GHz of the frequency-doubled LO is used to attain a 3-MHz IF when compared with the 35.5-GHz signal frequency of half of the Ka-band 8×2 antenna array(Fig. 7(a)).

The amplitude of the resulting down-mixed 3-MHz RF signal(transverse near-field components), demodulated in the low-frequency photodetector, are plotted versus

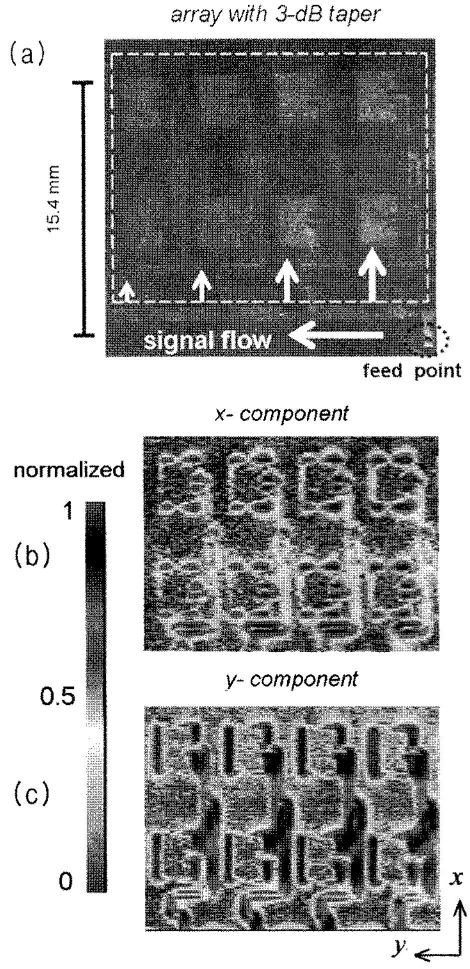

Fig. 7. EO amplitude maps of the transverse field components of a Ka-band(35.5 GHz) patch-antenna array (P_{in}=+5 dBm). (a) Photograph of 4×2 array(the dashed box is the scan area), (b) x-transverse electric field distribution, (c) y-transverse electric field distribution.

position in Fig. 7 for a 4×2 section of the array. An SNR of >30 dB was achieved, allowing detailed resolution of the fields along the edges of the antennas and their feed network.

As expected from the discussion of Fig. 1, the electric fields diminish as they flow from the feed line to the farthest array element(It should be noted that the power flow is proportional to the square of the electric fields, and thus the actual power diminishes more than it appears to in Fig. 7). For each individual patch antenna, the x-components of the adjacent electric fields were observed to be out-of-phase(not shown), and thus fields of these polarizations were expected to destructively combine in the far field. For the y-components of the electric fields, the spatial field components were found to be in-phase, constructively combining to yield the dominant far-field polarization. In array antennas, phase matching is crucial to enhancing antenna performance. For this array, matching was realized by meandering the feed lines to produce the same phase delay among the sub-array antenna pairs shown in Fig. 2. Thus, the y-components of the electric fields in the far field produced by the array are enhanced, while the x-components are cancelled out. Further detailed analyses for lower-frequency antennas, such as in the UHF-[11], X-[5],[8], and K-[8] bands, have been reported in previous publications.

Ⅴ. Conclusion

We have presented a simple and efficient high-frequency electro-optic sensing system for a Ka-band microstrip array antenna that was designed for wide-range detection of moving targets. The serial-feed unit(2×1 sub-array) was extended along the E-plane to form a pair of 8×2 arrays with the simultaneous lobing method. The narrow feeding and impedance phase-matching network lines for the millimeter-wave antenna were investigated using the minimally invasive EO sensing technique. The detailed principle and multi-stage carrier suppression technique that allowed efficient millimeter-wave EO sensing were both presented. The measured signal flow of the current-induced near-electric fields corroborated the performance of the unique antenna feed-matching network, as well as the origin of its far-field radiation.

References

[1] K. Yang, G. David, S. Robertson, J. F. Whitaker, and L. P. B. Katehi, "Electro-optic mapping of near-field distributions in integrated microwave circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2338- 2343, Dec. 1998.

[2] Z. Jiang, X.-C. Zhang, "Terahertz imaging via electrooptic effect", *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2644-2650, Dec, 1999.

[3] K. Sasagawa, A Kanno, T. Kawanishi, and M. Tsuchiya, "Live electrooptic imaging system based on ultraparallel photonic heterodyne for microwave near-fields", *IEEE Trans. Microwave Theory Tech.*, vol. 55, pp. 2782-2791, Dec. 2007.

[4] J. J. Kang, D. J. Lee, C. C. Chen, J. F. Whitaker, and E. J. Rothwell, "Compact mobile RFID antenna design and analysis using photonic-assisted vector near-field characterization", *IEEE International Conference on RFID*, pp. 81-88, Apr, 2008.

[5] D. J. Lee, M. H. Crites, and J. F. Whitaker, "Electro-optic probing of microwave fields using a wavelength-tunable modulation depth", *IOP Meas. Sci. Tech.*, vol. 19, pp. 115301-115310, Sep. 2008.

[6] J. Huang, "A parallel-series-fed microstrip array with high efficiency and low cross polarization", *Microwave and Optical Tech. Lett.*, vol. 5. no 5, pp. 230-233, May 1992.

[7] Y. J. Lee, M. S. Jung, W. S. Park, and J. H. Choi, "Design of a 35 GHz microstrip tapered-array antenna with wide detection range", *Microwave and Optical Tech. Lett.*, vol. 29, no. 4, pp. 276-280, May 2001.

[8] D. J. Lee, J. F. Whitaker, "Bandwidth enhancement of electro-optic field sensing using photonic downmixing with harmonic sidebands", *Opt. Express*, vol. 16, pp. 14771-14779, Sep. 2008.

[9] K. Sasagawa, M. Tsuchiya, "Modulation depth enhancement for highly sensitive electro-optic RF near-field measurement", *Electron. Lett.*, vol. 42, pp. 1357-1358, Nov. 2006.

[10] D. J. Lee, J. F. Whitaker, "Optimization of electro-optic sideband modulation in optical-heterodyne-down-mixed sensing of microwave-fields", *Appl. Opt.*, vol. 48, no. 9, pp. 1583-1590, Mar. 2009.

[11] D. J. Lee, J. J. Kang, and J. F. Whitaker, "Vector near-field measurements using optimized electrical and photonic down-conversion", *IEEE Trans. Microwave Theory Tech.*, vol. 56, pp. 3231-3238, Dec. 2008.

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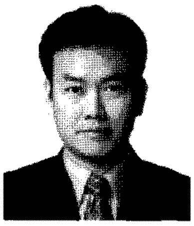

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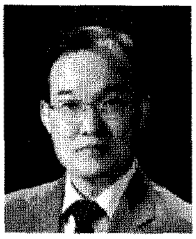

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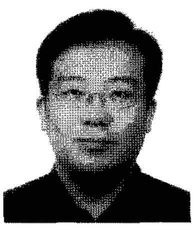

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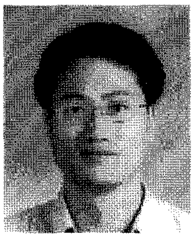

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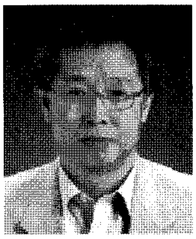

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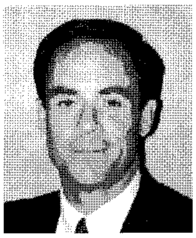

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