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Planar Waveguide Arrays for Millimeter Wave Systems

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SUMMARY Design of high gain and high efficiency antennas is one of the key challenges in antenna engineering and especially in millimeter wave communication systems. Various types of planar waveguide arrays with series-fed traveling wave operation have been developed in Tokyo Tech with the special focus upon efficiency enhancement as well as reduction of fabrication cost. In this review, four kinds of single layer waveguide arrays characterized with the series fed travelling wave operation are surveyed first. To cope with the bandwidth narrowing effects due to long line effects associated with the series fed operation, authors have introduced partially corporate feed embedded in the single layer waveguide. They further extended the study to cover fully corporate feed arrays with multiple layer waveguide as well; a new fabrication technique of diffusion bonding of laminated thin plates has the potential to realize the low cost mass production of multi-layer structures for the millimeter wave application. Secondly, the novel methods for loss evaluation of copper plate substrate are established for the design of post-wall waveguide arrays where dielectric loss and conductor loss is determined in wide range of millimeter wave band, by using the Whispering gallery mode resonator. This enables us to design the planar arrays with the loss taken into account. Finally, the planar arrays are now applied to two kinds of systems in the Tokyo Tech millimeter wave project; the indoor short range file-transfer systems and the outdoor communication systems for the medium range backhaul links. The latter has been field-tested in the model network built in Tokyo Tech Ookayama campus. Early stage progress of the project including unique propagation data is also reported.

key words: *array design, loss evaluation, diffusion bonding, millimeter wave, indoor file-transfer system, outdoor communication system*

1. Introduction

Design of high gain and high efficiency antennas is one of the key challenges in antenna engineering and especially in millimeter wave communication systems [1], [2]. The planar passive arrays using conventional transmission lines such as microstrip and triplate lines generally suffer from the increasing conductor loss in millimeter wave. For example, it is hard to find the report of planar arrays with more than 30 dBi in 60 GHz band or higher [3], [4], where the efficiency is relatively low and the assist of active devices was also discussed [5]. To cope with the substrate loss, bulky reflectors or horns are the traditional but still popular selection for high gain use [3]. Waveguide feed has the potential in terms of low loss and slimness and is adopted in works [6]–[9] but the realization of the simple and low cost structure for civil use remains key issue. The authors have developed high-efficiency and mass-producible planar slot array antennas using unique single-layer waveguide structures [10]–[13]. Four types of planar waveguides, all belonging to single-layer waveguide, are structurally quite simple and low cost while they inherit low loss characteristics from waveguides. They are leading candidates for high-gain planar antennas in high frequency wireless systems. Recent studies are directed to system integrations for microwave and millimeter wave systems, while the fundamental researches such as the bandwidth enhancement and the loss identification /reduction are still underway.

In this paper, four kinds of single layer waveguide arrays developed in these decades are summarized first. As common features, these are characterized by high efficiency in high gain region, simple structure for low cost fabrication, and the bandwidth narrowing due to the long line effects associated with the series fed travelling wave operation. To cope with this disadvantage and to utilize the huge bandwidth in millimeter wave, the drastic changes in series feeder of arrays is indispensable. Second part of this paper briefly explains the works for inclusion of partially or fully corporate feeds in the planar waveguide arrays without excessive increase of the loss and the fabrication costs. Single-layer slotted waveguide arrays with an embedded partially corporate feed [14] and double-layer corporate-feed waveguide slot arrays by diffusion bonding of laminated thin metal plates are presented [15]. By the way, dielectric loss as well as conductor loss in the substrate is notable in millimeter wave band, but this is not easily obtained. Basic but still difficult challenges in substrate antennas design are to assess the material and conductor loss. Authors have established a novel procedure for extraction of material loss parameter by using the Whispering gallery mode resonator [16], [17]. The parameters extracted by this method are verified by the transmission line loss measurement and are now used for identifying the loss factors in post-wall waveguide arrays.

The planar arrays developed above are now applied to two kinds of systems in the Tokyo Tech millimeter wave project entitled “RF coexisting technology on high speed baseband CMOS for Millimeter wave radio systems”; the indoor short range file-transfer systems and the outdoor communication systems for the medium range backhaul links [18]. The latter has been field-tested for rain attenuation monitoring in the model network built in Tokyo Tech Ookayama campus. The paper covers early stage progress of the project including unique propagation data as well

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[19].

In this paper, a 20×20-element double-layer antenna with a partially-corporate feed is designed in 39 GHz band, and fabricated by diffusion bonding of thin copper plates. The high potential and feasibility of multi-layer waveguide antennas with high-performance is to be demonstrated.

2. Planar Waveguide Arrays for Millimeter Wave Systems

2.1 Waveguide Arrays for High Gain and High Efficiency in Millimeter Wave Band

Various applications of millimeter waves are listed in Fig. 1 as functions of the frequency and the antenna gain, where systems in lower frequencies and with small antennas are not included [13]. In high gain planar antennas, the efficiency is dominated by the loss in the transmission line, that is, conductor loss, dielectric loss and unwanted radiation loss as is expressed in Fig. 2. The conductor loss becomes dominant in millimeter wave, which could be reduced if the height of the transmission line is increased. In open structures such as the microstrip and triplate lines, however, larger height results in increase of unwanted radiation loss. The waveguides, on the contrary, are free of radiation loss and the thickness could be increased to reduce the conductor loss; they are low loss and are suitable for LAN, Radar and Subscriber radio systems. The authors have developed high-efficiency and mass-producible planar slot array antennas using unique single-layer waveguide structures. Four types of planar waveguides, all belonging to single-layer waveguide, are structurally quite simple as are shown in Fig. 3 [12], [13], while they inherit low loss characteristics from waveguides. They are leading candidates for high-gain planar antennas in high frequency wireless systems. The efficiency of planar antennas reported in the literature is summarized in Fig. 4 as functions of the frequency and the antenna gain. The efficiency of single layer slotted waveguide arrays in Fig. 3 is much higher than those of microstrip and triplate ones; the high potential of the single-layer waveguide arrays in high gain and high frequency applications is fully demonstrated.

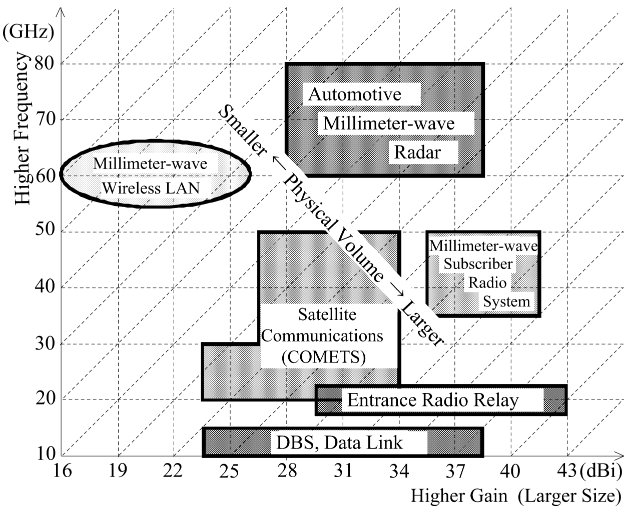

Fig. 1 High-frequency and high-gain applications for planar arrays.

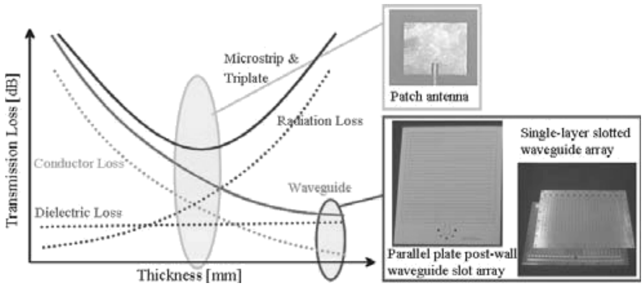

Fig. 2 Loss factors of transmission lines as functions of their thickness.

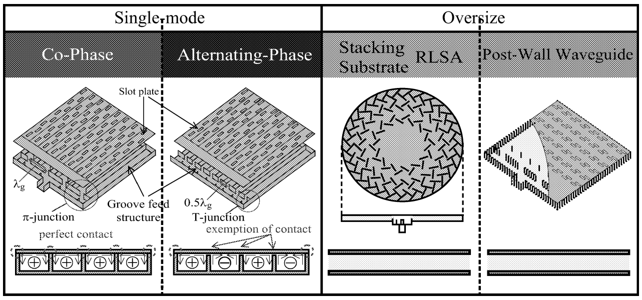

Fig. 3 Four types of single-layer slotted waveguide arrays.

2.2 Four Kinds of Single Layer Waveguide Arrays with Series Feeds

(**Co-phase feed**) The multiple-way power divider for single-mode waveguides with co-phase excitation consist of series of -junctions spaced by a wavelength as in Fig. 5. Figure 6 indicates only two components that are a slotted plate and a base plate with corrugation are the parts of this array. This array was commercialized for the mobile DBS reception in 12 GHz band. The peak gain of 35.9 dBi and the efficiency of 75.6% at 22.15 GHz were realized [20]. The 76 GHz band arrays for automotive radar are also tested and 35.5 dBi with 64% efficiency was reported. It is noted that the electrical contact between the narrow walls on the bottom plate and the slot plate should be perfect.

(**Alternating phase feed**) In alternating phase fed arrays, the power divider with series of T-junctions separated by half the wavelength excites adjacent waveguides out of phase by 180 degree as in Figs. 6 and 7; electrical contact between the narrow walls and the slot plate is not necessary. So, drastic reduction of loss as well as cost for fabrication has been realized. The leakage at the periphery of the aperture was suppressed by the choke in realistic arrays. No less than 60% efficiency and 32.4 dBi gain was reported in 26 GHz band antenna with mechanical contact by simple screws [21], [22]. The alternating-phase-fed waveguide array has realized 57% efficiency with 34.8 dBi gain

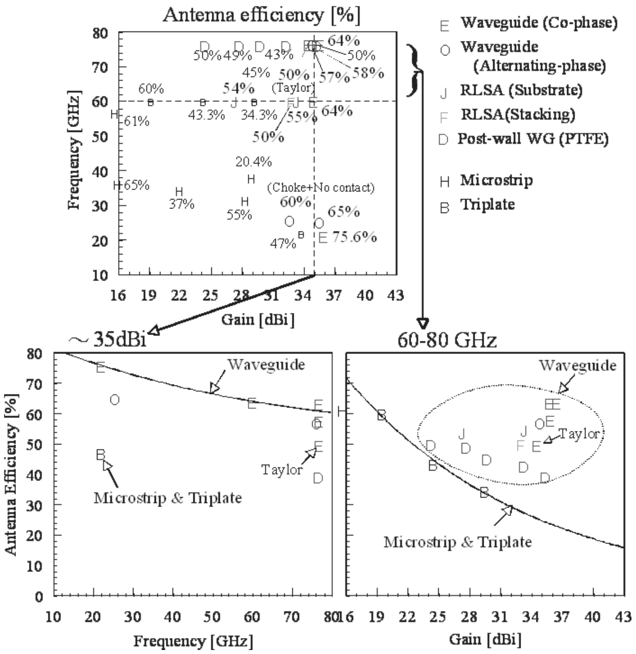

Fig. 4 Antenna efficiency for different types of planar antennas as functions of the gain and the frequency.

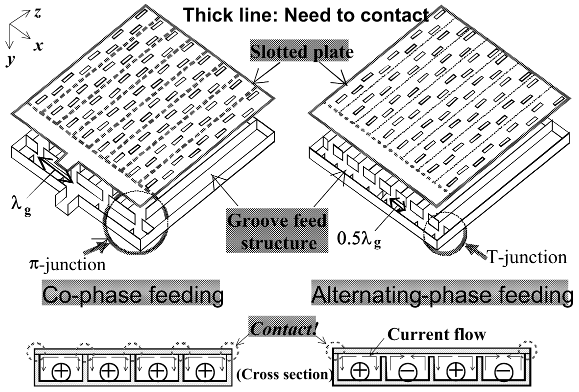

Fig. 5 Co-phase and alternating-phase fed single-layer slotted waveguide arrays with single-mode operation.

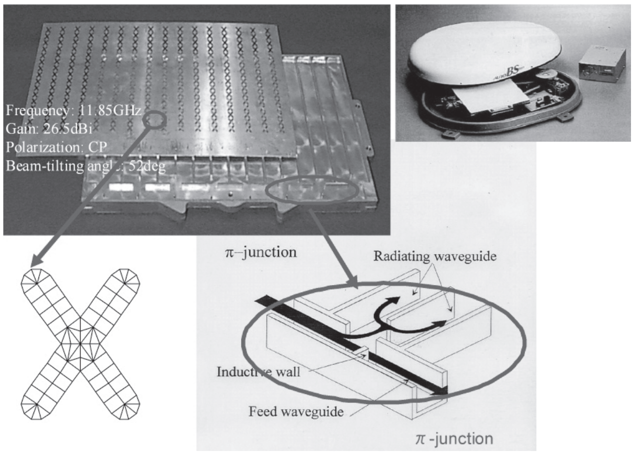

Fig. 6 Co-phase fed single-layer waveguide cross-slot array for mobile DBS reception: detailed design of a cross slot and the π-junction in the feed waveguide as two key components.

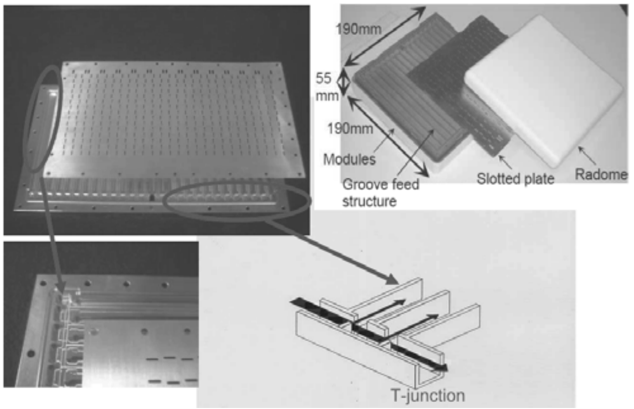

Fig. 7 Alternating-phase fed single-layer slotted waveguide array for fixed wireless access terminal: microwave choke around the periphery and T-junction in a feed waveguide.

at 76.5 GHz in measurement.

(**RLSA**) Parallel plate structure operating in TEM cylindrical wave excitation has no side-walls and assures the lowest transmission loss among the four. Since it is oversized and the slot pair should be designed so as not to excessively perturb the global traveling wave operation. It is already commercially mass-produced in the form of circular radial line slot antennas (RLSA) fed by a coaxial cable for 12 GHz DBS reception as in Fig. 8. For millimeter wave application, 52% efficiency at 32 dBi was accomplished in 60 GHz band [23], [24].

(**Post-wall Waveguide**) Another version of rectangular parallel plate antenna presented in Fig. 9 is also developed using plane TEM wave generator called “post wall waveguide” [25]. The antenna is fabricated using a thick grounded dielectric substrate and densely arrayed metalized via-holes (posts: 0.3 mm diameter) which replace conducting narrow walls. It can be easily made at low cost by conventional PCB (print circuit board) fabrication techniques such as via-holing, metal-plating and etching. Car radar antennas in 70 GHz band are now tested and 25–34 dBi are covered with the efficiency 40–50% while about 60% was realized in 60 GHz band [26]. Millimeter wave RF modules using a 21 dB post-wall array are realized as in the Photo in Fig. 9 [27]–[30].

Series-fed traveling wave operation in single mode and oversized waveguide is the common feature of the above arrays. Unfortunately, as the antenna size increases, the bandwidth becomes narrower due to long line effects. To remedy this weak point, partially or fully corporate feed may be introduced in the single layer waveguide arrays; here, the corporate feeds always widen the bandwidth at the sacrifice of the structural simplicity and it is important that the increase of loss as well as the fabrication cost should be avoided.

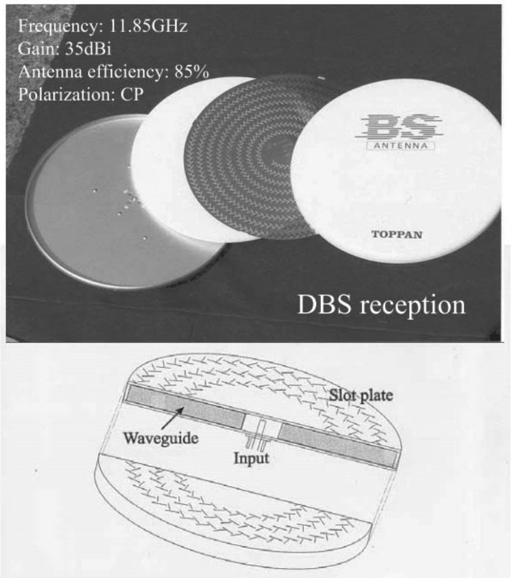

Fig. 8 Radial line slot array (RLSA) for DBS reception.

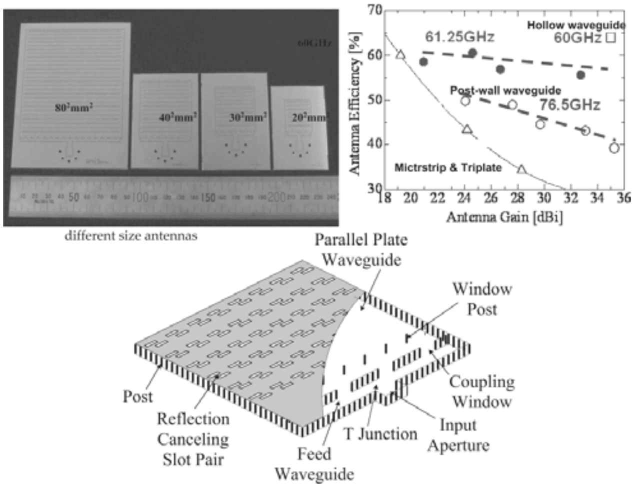

Fig. 9 Parallel plate post-wall waveguide slot arrays and the efficiency degradation with the increase of the aperture size.

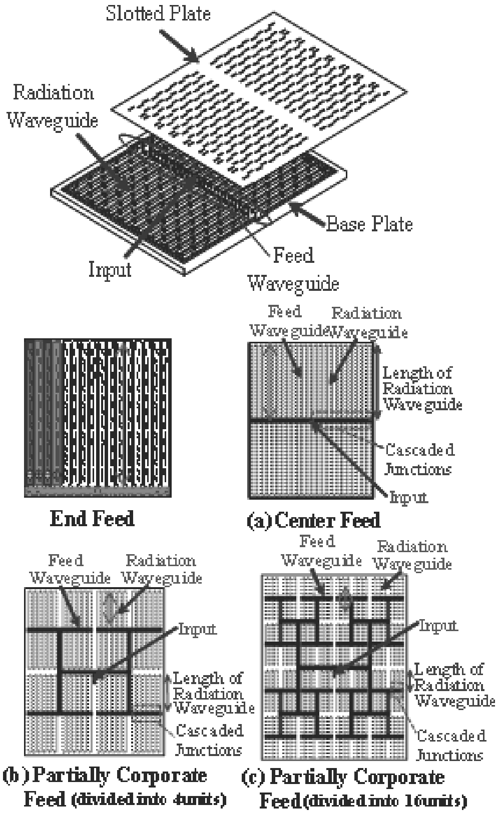

Fig. 10 Alternating-phase fed single-layer slotted waveguide arrays with embedded partially corporate feeds.

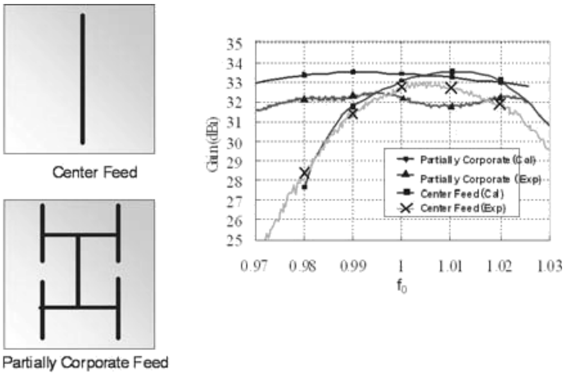

Fig. 11 Enhanced bandwidth of gains for partially corporate feed antennas.

2.3 Bandwidth Enhancement of Waveguide Arrays by Introducing Corporate Feeds

2.3.1 Single Layer Waveguide Arrays with Embedded Partially Corporate Feed

Corporate feed realizes co-phase irrespective of frequency and has the widest bandwidth in principle, while the series feed suffers from phase errors linearly dependent upon frequency and is narrow banded. In terms of feed line length averaged over the array, the latter has the shorter length and the higher efficiency than the former. Authors have been seeking the efficiency more than the bandwidth and developed series feed arrays; a partially corporate feed is the combination of the two and provides the intermediate bandwidth and feed loss. Authors proposed the embedded partially corporate feed for the single-layer waveguide arrays as are shown in Fig. 10 [14]. The prevalence of corporate feed results in reduced feed line length difference and wider bandwidth. Figure 11 demonstrates the bandwidth widening effects by this technique; the bandwidth for partially corporate feed is much wider than that of center feed arrays. Generally the array gain and the bandwidth, which are related in terms of the aperture size in principle, can now be designed independently. In order to suppress the increasing non-radiating area above the embedded feeder, we designed E-to-H-plane power divider with very small blockage.

2.3.2 Multi-Layer Waveguide Arrays with Corporate Feed by Diffusion Bonding of Laminated Thin Metal Plates

We introduced a new fabrication process of diffusion bonding of laminated thin metal plates as is shown in Fig. 12 [10], [15]. It brings about the multi-layer structure with perfect electrical contact and without causing the serious increase of fabrication cost; double-layer or triple-layer feed waveguides could be realized in low cost and corporate feed gives us the wider bandwidth. One example of double layer with partially corporate feed is presented in Fig. 13. Extremely high antenna efficiency as well as the wide bandwidth 3 GHz are obtained at 38 GHz band [30], [31].

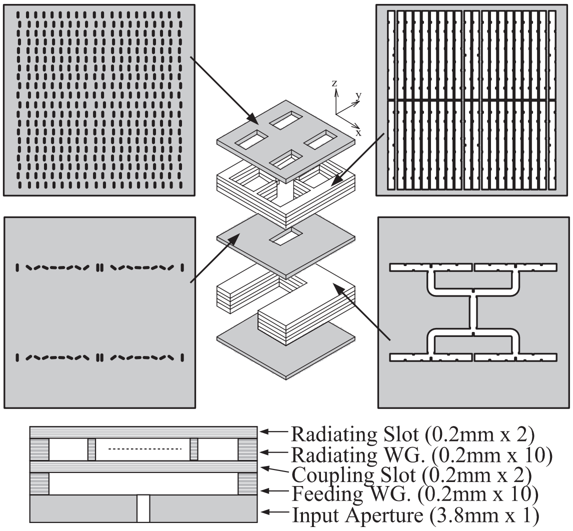

Fig. 12 Partially-corporate feed double-layer waveguide array by diffusion bonding of laminated thin plates.

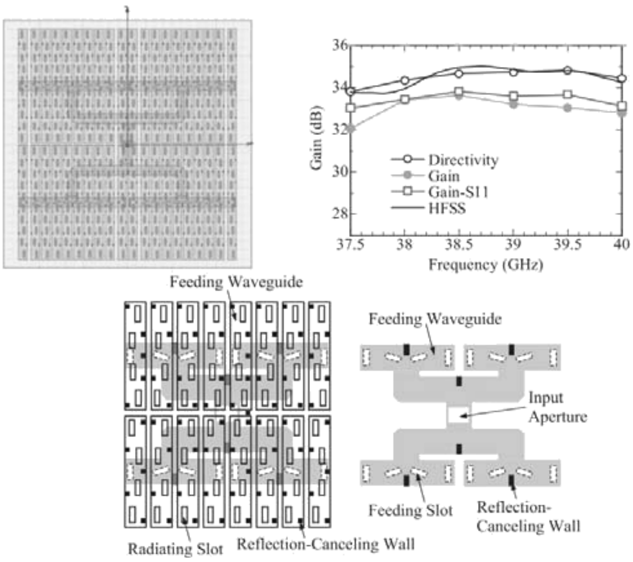

Fig. 13 Enhanced bandwidth of Gain of partially-corporate feed double-layer antenna.

3. Substrate Loss Evaluations by using Whispering Gallery Mode Resonator of Post Wall Waveguide Arrays

Authors are developing post wall waveguide arrays using the substrate which drastically reduces the fabrication cost of waveguide structure. In millimeter wave applications, the dielectric loss and the conductor loss become notable and should be estimated carefully. Unfortunately, most of the data are available only for low frequencies. We have developed a unified procedure for evaluating the dielectric loss and the conductor loss of the substrate in millimeter-wave frequencies, which is presented in Figs. 14 and 15 [17], [32]. The resonant frequencies and the Q-factors of the substrate without the metal are measured by using Whispering gallery mode resonator. The complex dielectric constants are estimated by referring to the data provided by the mode matching method. Then the second measurement for the substrate with the metals provides us the resonant frequencies and the Q-factors perturbed by the finite conductivity. They are numerically predicted by the HFSS simulator as well, as functions of the conductivity; the comparison of these determines the estimation of conductivity of the metal. Fig. 16 demonstrates the fine agreement of the measured and the estimated transmission loss for the microstrip lines and the post wall waveguides with various height of the substrate [32]. Two important points should be emphasized with these results.

- (1) The material constant as well as the loss parameter could be discussed in quite wide range of millimeter wave frequency. This is the advantage of Whispering gallery mode resonator using oversized waveguide.
- (2) Transmission line loss is accurately predicted by the measured material parameters; the former is specific for the individual transmission line structure while the latter is more general. The reasonable agreement for lines of different types, of various heights and in quite wide frequency range, seems remarkable. It is noted that the radiation loss grows for large height in microstrip lines as in Fig. 2 and the low loss characteristics of the post-wall waveguide are also confirmed in Fig. 16.

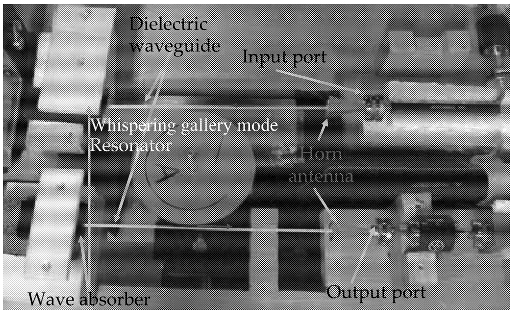

Fig. 14 Test antenna made of copper in 39 GHz band.

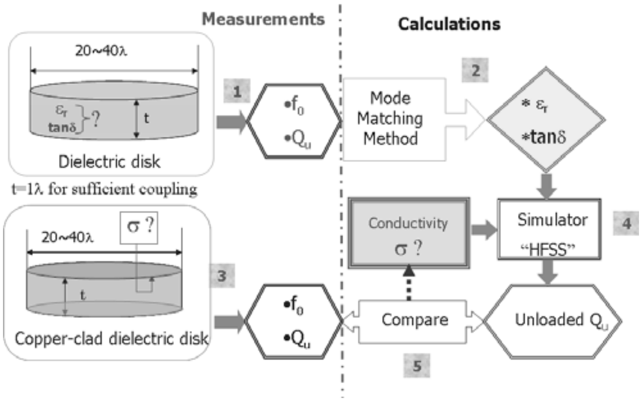

Fig. 15 Test antenna made of copper in 39 GHz band.

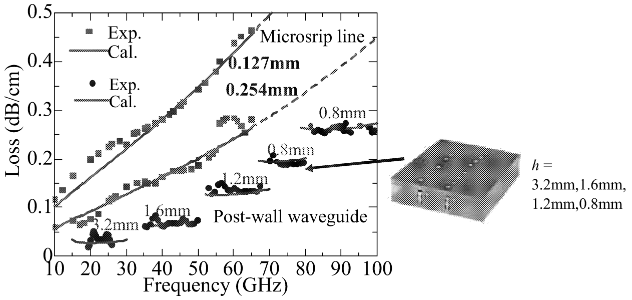

Fig. 16 Test antenna made of copper in 39 GHz band.

4. Tokyo Tech Wireless-Fiber Project for Millimeter Wave Systems

The authors drive a Millimeter Wave Project from FY2007 and until FY2011. It includes the RF and Baseband Chips for realization of broadband wireless systems, which was named as "RF coexisting technology on high speed baseband CMOS for Millimeter wave radio systems" and is supported by Government (MIC) as well as Industry's participation. Outdoor and indoor communication systems beyond Gbps are designed based upon these ICs as well as the planar waveguide antennas. The outdoor system will be tested/demonstrated in Tokyo Tech Ookayama-campus millimeter wave model network, which models the medium range backhaul links for XGP. This paper discusses the overview of this project.

Figure 17 presents the targeted systems in the project, where the outdoor and the indoor ones are plotted in terms of the frequency, data rate and the distance. The usage models are also demonstrated in Fig. 18, where the entrance radio systems for the backhaul of the XGP (or WiMAX) base stations (−1 km) and the high speed file transfer (−1 m) are for the outdoor and the indoor application, respectively. These are characterized by the unique single layer waveguide array for the outdoor systems and the post wall antennas for the indoor systems. The project team consists of Tokyo Tech members in the areas of the antennas, circuits and signal processing, electronics companies JRC for outdoor system, SONY for indoor system, AMMSYS for packaging and WILLCOM, the PHS operator. The critical components in MM-wave wireless systems are RF and Baseband chips as well as the analog and digital signal processing, which have been drastically developed by the Silicon CMOS technology [33], [34]. Figure 19 explains the CMOS chip development scenario in 5 years. For the outdoor system, 90 nm rule chip is adopted with the combined use of compound semiconductor materials in terms of cost and high power, while in the indoor system, 65 nm rule for RF and 40 nm rule for baseband are used in terms of cost, low power and high speed. We expect that RF chips using 40 nm rule may be available in the future but is still expensive and needs longer fabrication cycle for the university.

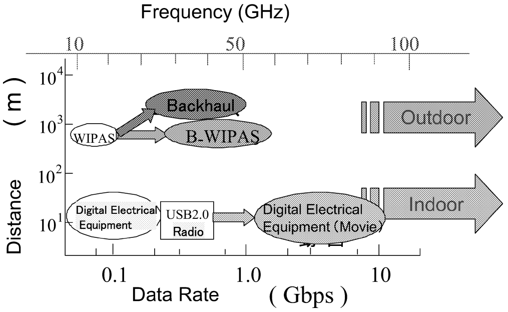

Fig. 17 Frequency, data rate and distance for target systems in Tokyo Tech Wireless-Fiber Project: fixed wireless access systems in 38 GHz band and short range file transfer in 60 GHz band.

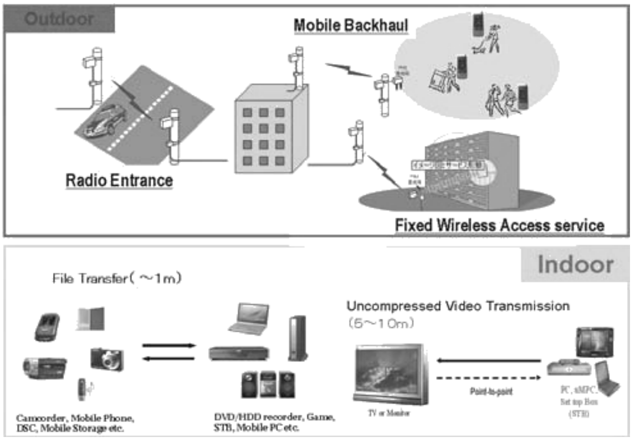

Fig. 18 Outdoor and indoor applications in millimeter-wave band; 38 GHz band fixed wireless access systems as backhaul or entrance and 60 GHz band short range file transfer.

For the short range file-transfer system, the handy terminal consists of two chips, 60 nm RF and 40 nm baseband as is depicted in Fig. 20. It has the post wall waveguide antennas with parasitic directors which have the 6 dB gain radiation in the lateral direction or in the plane of the substrate as in Fig. 21 [35]. Figure 22 shows the RF/BB CMOS-IC block diagram. All the components for 60 GHz CMOS RF-frontend (Tx/Rx) are developed by using the 65 nm process (Fujitsu) and are under measurement. As for the BB chips, analog BB circuits such as VGA, ADC/DAC and PLL

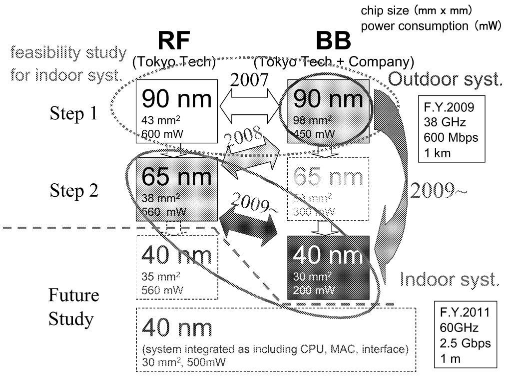

Fig. 19 CMOS chip development for RF and BB and technologies adopted in the Tokyo Tech Wireless Fiber Project.

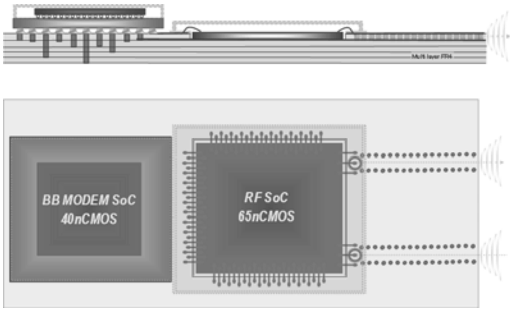

Fig. 20 Assembly image of 60 GHz indoor system.

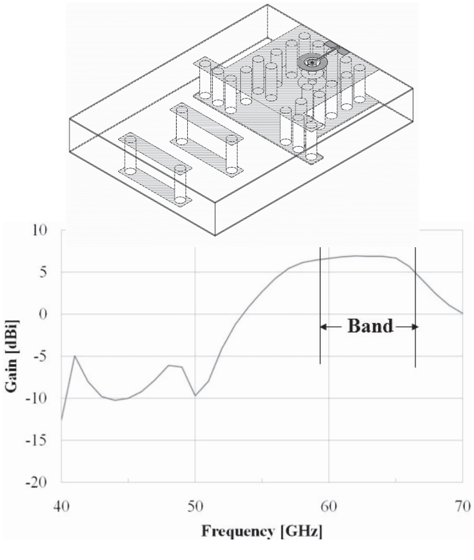

Fig. 21 Predicted gain of the post wall waveguide antenna with directors for Lateral-radiation.

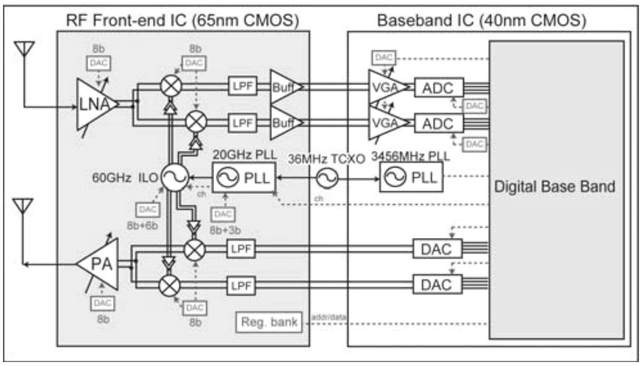

Fig. 22 Configurations for 40 nm BB and 65 nm RF circuits.

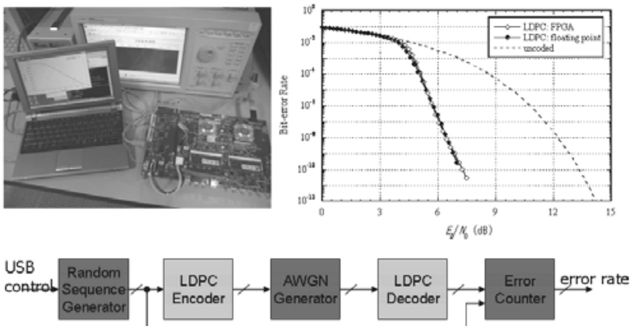

Fig. 23 BB signal processing test using 90 nm FPGA; BER rate of LDPC (1440, 1344) code evaluated using hardware decoder implemented on an FPGA. No floor was observed above bit-error rate of 3×10^{-11}.

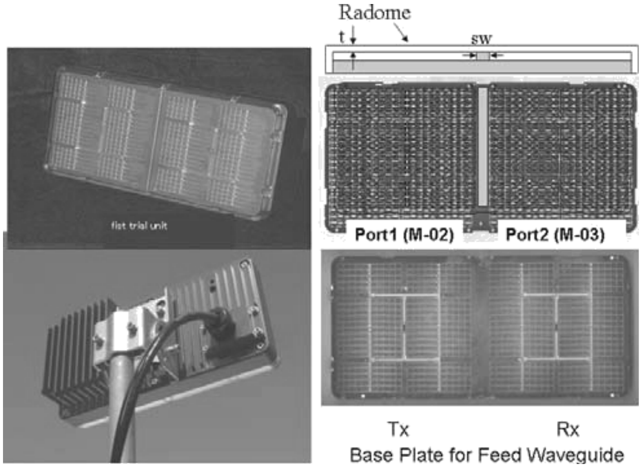

Fig. 24 38 GHz-600 Mbps Wireless terminals. Two arrays with the same polarization are arranged with the isolation more than 65 dB.

together with Digital circuit including LDPC are designed using 45 nm process (TSMC). Figure 23 presents the signal processing test using 95 nm FPGA; BER rate of LDPC (1440, 1344) code evaluated using hardware decoder implemented on an FPGA. No floor was observed above bit-error rate of 3×10^{-11}.

For the outdoor system in 38 GHz band, we develop a compact one-box type wireless terminal which accommodates two (Tx and Rx) arrays as is shown in Fig. 24 [36]. The array has the partial corporate feed explained before for wider bandwidth. The isolation more than 65 dB is realized in the same polarization by the conducting wall between apertures and also the radome as in Fig. 24.

The radiation characteristics, return loss, gain and isolation are presented in Fig. 25. Figure 26 presents the mixed signal SoC developed for 38 GHz-640 Mbps includ-

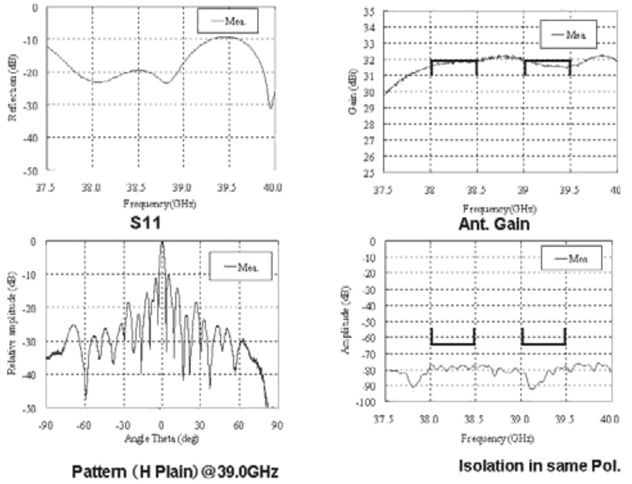

Fig. 25 Antenna characteristics of 38 GHz band arrays. (alternating phase fed arrays with embedded partially corporate feed).

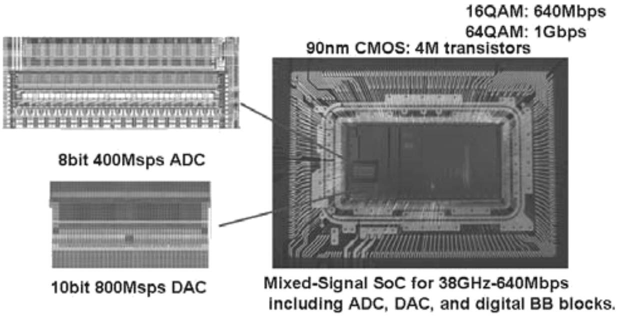

Fig. 26 ADC and DAC developed for 38 GHz-640 Mbps systems.

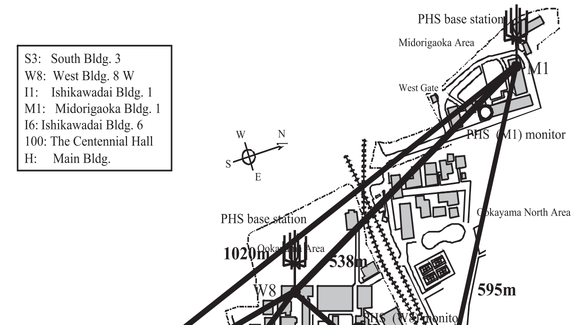

Fig. 27 TokyoTech model network; 20 wireless terminals on 7 buildings, 10 links (100 m–1000 m), 3 PHS base stations and 3 PHS monitors are in operation since 2007, while XGP (next generation PHS) base stations have been installed. All buildings are equipped with rain-rate monitors.

ing ADC, DAC and digital BB blocks. It consists of 4M transistors based on 90 nm process (FUJITSU). The outcomes from this project will be demonstrated in the MM-wave model network constructed in Tokyo Tech Ookayama Campus [19]. Ten point-to-point links initially in 25 GHz and now in 38 GHz have 100 m–1 km length and are connected in mesh as in Fig. 27, where three out of seven base stations are co-located with the 2 GHz PHS (now replaced with XGP) base stations. The field strength, the BER, and the rain rate monitoring system started in 2008 with 25 GHz system which has been replaced with 38 GHz system in 2010. The influence of millimeter wave network quality and rain rate upon the PHS throughput has been recorded every five second. The fading simulator is also developed to reproduce these events in laboratory.

5. Conclusions

Four types of single layer waveguide slot arrays are reviewed. Typical systems for high gain and high frequency applications are demonstrated. The fabrication technique by diffusion bonding of laminated thin metal plates is introduced to realize multi-layer slotted waveguide array for larger bandwidth. Recent progress in Tokyo Tech MM-wave project is introduced which verifies the feasibility of millimeter wave technologies, such as antennas, RF and baseband chips including RF CMOS, digital signal processing for phase noise suppression, packaging etc., as well as the propagation test of the outdoor systems, for commercial use.

Acknowledgement

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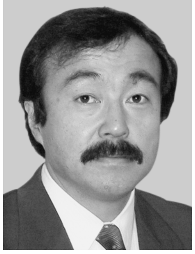

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