PAPER

Design of mm-Wave RLSAs with Lossy Waveguides by Slot Coupling Control Techniques

Tung NGUYEN[†a)], ***Student Member*****, Jiro HIROKAWA**[†]**, Makoto ANDO**[†]**,** ***Fellows*****,**
and **Manuel SIERRA CASTAÑER**[††]**,** ***Nonmember***

SUMMARY This paper discusses how to design a Radial Line Slot Antenna (RLSA) whose waveguide is filled with high loss dielectric materials. We introduce a new design for the aperture slot coupling synthesis to restrain the dielectric losses and improve the antenna gain. Based on a newly defined slot coupling, a number of RLSAs with different sizes and loss factors are analyzed and their performances are predicted. Theoretical calculations suggest that the gain is sensitive to the material losses in the radial lines. The gain enhancement by using the new coupling formula is notable for larger antenna size and higher loss factor of the dielectric material. Three prototype RLSAs are designed and fabricated at 60 GHz following different slot coupling syntheses, and their measured performances consolidate our theory.
key words: *lossy waveguides, radial line slot antenna, millimeter wave, coupling factors*

1. Introduction

In the past few decades, as the growing demands of ground-satellite communications, many researches focusing on the satellite onboard antennas have been conducted. A high gain is always required for a satellite onboard antenna since its high EIRP means a high quality link and a size and cost reduction of receiving dishes on earth stations. The most common antennas used in satellite communications are parabolic reflectors. They offer high gain, wide band, and low fabrication cost. However, conventional parabolic reflectors (paraboloids or dishes) suffer from a large volume of the antenna system including the reflector, the feed horn and sometime the subreflector, which results in a heavy weight and difficulties in manufacture and installment on a satellite.

To deal with this issue, planar antennas, which allow size and cost reductions, have been considered as the best candidate to replace the reflectors [1]. Moreover, with the development of advanced technologies such as printed circuit board (PCB) and high precision etching techniques in the past few years, planar slotted array antennas have become an effective choice for many satellite and millimeter-wave applications.

Radial Line Slot Antenna (RLSA) is a planar slot array antenna that utilizes the oversized radial waveguide as the feeding network and narrow slot as the radiating element. RLSA is well known for its high gain, high efficiency, and compact structure. The first RLSA was designed and commercialized for DBS reception at 12 GHz [2], and followed by a number of applications such as RLSAs for power transmission [3], plasma excitation in semiconductor processing [4], radars for collision avoidance [5], and radio access networks in the millimeter waveband [6]. Recently, RLSAs that can realize shaped beam [7], and high gain - lightweight RLSA [8] were studied for satellite onboard uses.

In 2010, a lightweight RLSA with a honeycomb structure for X-band operation was designed, manufactured, and successfully mounted on the Japanese satellite called "*Planet-C-Akatsuki*" [8]–[10]. The key improvement in this antenna was the use of a honeycomb structure as the dielectric spacer to reduce the antenna weight. As result, a 900 mm diameter RLSA weights only about 1 kg, which is very attractive for a satellite onboard application. Motivated by this success, we continued to develop a 32 GHz RLSA with honeycomb structure in part of the "*Hayabusa 2*" project of JAXA [11]. Different from *Planet-C*, the honeycomb structure fabricated by NoMEX® fiber, which has cell sizes small enough for mm-wave, suffers a great loss of about 0.014~0.018 dB/mm, and it degrades the antenna performance considerably [12]–[14]. Nevertheless, demands for high gain and lightweight planar antennas in mm-wave are rapidly increasing. Therefore, researches to make use of lightweight, lossy materials such as NoMEX® honeycomb seem unavoidable, and become urgent tasks for satellite antenna designers.

This paper proposes a new RLSA design that takes losses of the dielectric waveguide into account, or put differently, the lossy design of RLSA. The basic idea for improving the antenna gain is to adopt strongly coupled slots in the inner part of the aperture so that the energy is radiated early during radially outward travel. This early radiation can theoretically suppress the energy absorbed by the lossy waveguide, however, it also compromise the uniform radiation of RLSA. This "tradeoff" is mathematically optimized to maximize the antenna gain, and is detailed in Sect. 2. Section 3 shows numerical results for various cases with different antenna sizes, loss factors, and slot coupling distributions. Section 4 report measured performances of several prototypical RLSAs, which are designed and fabricated using a very lossy material at 60 GHz. Finally, conclusions are drawn in Sect. 5.

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[†]The authors are with Tokyo Institute of Technology, Tokyo, 152-8552 Japan.
[††]The author is with Universidad Plitécnica de Madrid, Madrid, Spain.
a) E-mail: tungnguyen@antenna.ee.titech.ac.jp
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2. Gain Optimization by the Slot Coupling Control

In RLSA operation, the use of an oversized radial waveguide filled with low loss dielectric materials is the main advantage for high antenna gain and efficiency, given the low conductor loss of the metal slot plate and reflection canceling effect of the unit radiating element [15]. Figure 1 shows a typical configuration of RLSA, and the antenna operation is illustrated in Fig. 2. A simple coaxial feeder attached to the bottom metal plate of the antenna at the center and creates a cylindrical wave travelling inside a radial waveguide filled with dielectrics. This travelling wave then excites the slots etched on the top plate and determines the uniformity of the radiated electrical field.

Takahashi et al. [16]–[18] have established a procedure to realize uniform amplitude and phase of the field radiated from the slots, which could assure high antenna gain if the dielectric loss was negligible. The key techniques of this procedure are:
- the slot coupling distribution to control the amplitude of the electrical field radiated from slots;
- the slot positioning to have an in-phase excitation and radiation.

The latter is normally realized by spacing slots in the radial direction a distance S_ρ of about one guided wavelength λ_g,

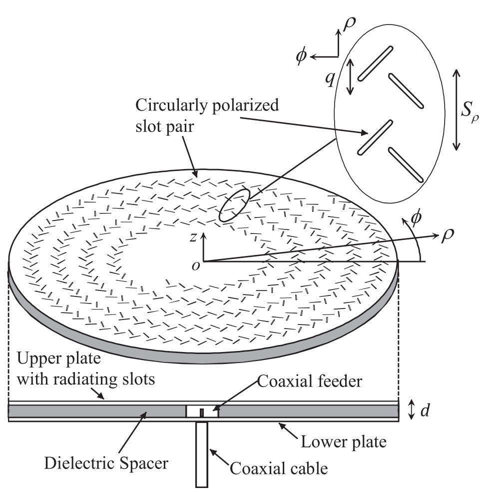

Fig. 1 Structure of a typical radial line slot antenna.

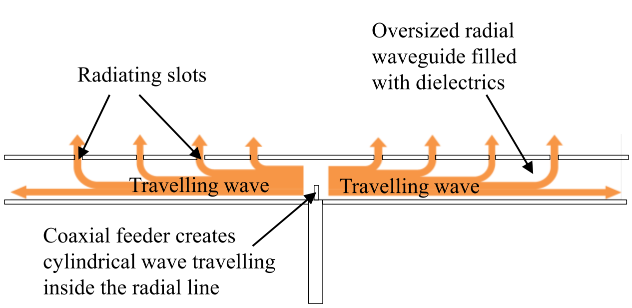

Fig. 2 Operation of a typical radial line slot antenna.

and some small adjustments of the slot angles to fix the radiating phase. On the other hand, the slot coupling distribution to control the radiated amplitude is theoretically calculated through an energy conservation model as shown in Fig. 3.

2.1 Energy Conservation Models

Figures 3(a), (b), and (c) demonstrate the energy conservation models for a lossless case, a general lossy case, and a lossy case in an incremental distance $\Delta\rho$, respectively. These figures suggest that if the dielectric losses are high, an *early radiation* is recommended to reduce the amount of energy absorbed by the lossy dielectric materials. However, doing so would sacrifice the uniformity of the radiated field, which means losing the directivity. Therefore, we have to look for a reasonable compromise between *early radiation* and *uniformity* for a gain optimization.

Considering a travelling wave in an incremental distance $\Delta\rho$ inside a lossy waveguide as illustrated in Fig. 3(c), the energy conservation can be expressed as,

$$\underbrace{P(\rho)}_{P_{in}}\,2\pi\rho d - \underbrace{P(\rho+\Delta\rho)}_{P_{out}}\,2\pi(\rho+\Delta\rho)d = 2\pi\rho\,\underbrace{P(\rho)\tau_r(\rho)\Delta\rho}_{P_{rad}} + 2\pi\rho\,\underbrace{P(\rho)\tau_l\Delta\rho}_{P_{loss}} \qquad (1)$$

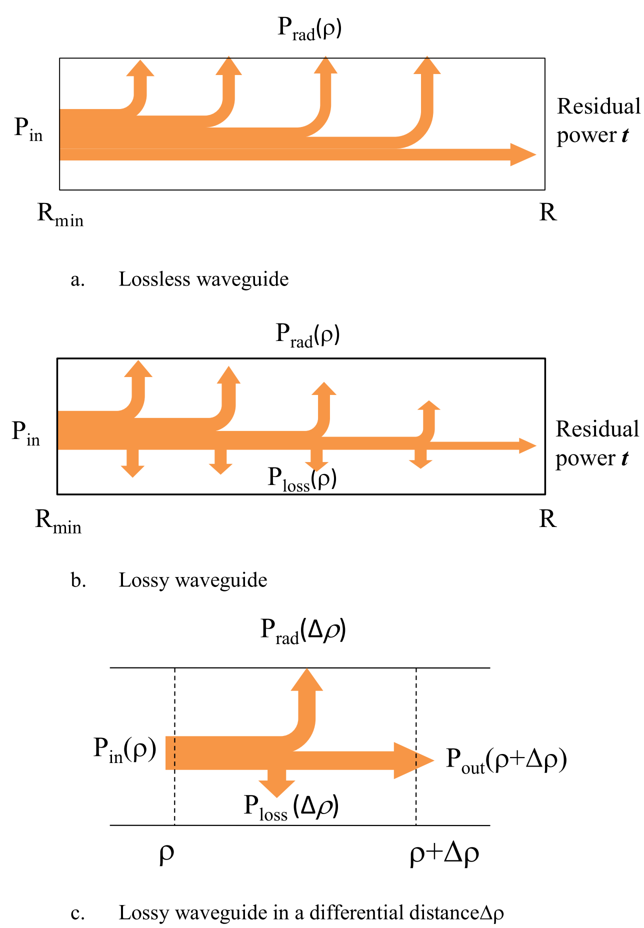

Fig. 3 Energy conservation models in lossless/lossy radial waveguides.

where d is the waveguide height and τ_r/τ_l is the ratio of the radiated/absorbed power to the inner power per unit length,

$$\begin{aligned}\tau_r(\rho) &= P_{rad}(\Delta\rho)/P_{in}(\rho)\\ \tau_l &= P_{loss}(\Delta\rho)/P_{in}(\rho)\end{aligned} \tag{2}$$

with P_{in}, P_{out}, P_{rad}, and P_{loss} denoted in Fig. 3(c).

In this paper, as we focus on the design of high gain RLSA, the residual power$t$ at the antenna rim is assumed to be negligible. For example, in the practical design of *Hayabusa 2* antenna [13], the residual power t is estimated to be less than 1%. For an RLSA with small aperture, the limitation of the coupling factor results in an considerably large residual power t at the termination (5~15%), and it should be taken into account in the process of arriving at the solution for the coupling factor distribution $\alpha_r(\rho)$ [16].

2.2 Coupling Factors

In RLSA design, each slot is represented by its length and width. And for a longitudinal slot whose width is much smaller than its length, a slot coupling or coupling factor α_r is mainly determined by the slot length. In term of the ratio of radiated to inner power at a radial distance ρ, the coupling factor is defined as,

$$\alpha_r(\rho) = \tau_r(\rho)/2d \tag{3}$$

According to Takahashi [16]–[18], the coupling distribution $\alpha_r(\rho)$ is the key factor to control the uniformity of the aperture distribution. In a lossless case, a coupling factor distribution,

$$\alpha_r(\rho) = \frac{\rho}{R_{\max}^2 - \rho^2} \tag{4}$$

with $R_{\max}$ is the antenna radius, would assure an uniform aperture illumination and the best antenna performance. Extensively, the conventional lossless case can be expanded to a general lossy problem by introducing a loss factor $\alpha_l = \tau_l/2d$ with τ_l defined in (2). Substituting the loss factor α_l and the coupling factor $\alpha_r(\rho)$ defined in (3) into (1), gives us a differential Eq. (5).

$$\frac{d}{d\rho}(P(\rho)\cdot\rho) = -2P(\rho)\cdot\rho\cdot[\alpha_r(\rho) + \alpha_l] \tag{5}$$

Solving (5) for the radiated power $P(\rho)$, we get,

$$P(\rho) = C\frac{1}{\rho}\cdot e^{-2\alpha_l\rho}\cdot e^{-2\int_0^\rho \alpha_r(r)dr} \tag{6}$$

Theoretically, if the phase is uniform over the aperture, the antenna gain at the bore-sight of an RLSA can be calculated as a function of coupling factor $\alpha_r(\rho)$ in straight-forward manner by,

$$G[\alpha(\rho)] = \frac{\left(\int_{\rho_{\min}}^{\rho_{\max}}\int_0^{2\pi} E(\rho)\rho d\phi d\rho\right)^2}{2\pi\rho_{\min}P(\rho_{\min})} \tag{7}$$

with $E(\rho)$ is the amplitude of the radiated field at a radial distance ρ.

$$E(\rho) = \sqrt{P(\rho)\alpha_r(\rho)} \tag{8}$$

Given the normalized incident power $2\pi\rho_{\min}P(\rho_{\min}) = 1$, (7) and (8) is simplified to (9),

$$G[\alpha(\rho)] = \left(\int_{\rho_{\min}}^{\rho_{\max}} \sqrt{P(\rho)\alpha_r(r)}\rho d\rho\right)^2 \tag{9}$$

where $\rho_{\max}$ and $\rho_{\min}$ stand for the position of the outermost and innermost slots, respectively. Substituting (6) into (9), we obtain the gain proportional to a function of coupling factor $\alpha_r(\rho)$.

$$f(\alpha_r,(\rho)) = \left(\int_{\rho_{\min}}^{\rho_{\max}} \sqrt{\alpha_r(\rho)\rho}\cdot e^{-(\alpha_l\rho+\int_0^\rho \alpha_r(r)dr)}\right)^2 \tag{10}$$

The condition to maximize the function $f(\alpha_r(\rho))$ is,

$$J[u] = \int_{\rho_{\min}}^{\rho_{\max}} \sqrt{\rho u'}e^{-u}e^{-\alpha_l\rho} \to \text{maximum} \tag{11}$$

with

$$u(\rho) = \int_{\rho_{\min}}^{\rho} \alpha_r(r)dr \tag{12}$$

Eq. (11) is then solved by the calculus of variations with the augmented function is

$$F[u] = -\sqrt{\rho u'}e^{-u}e^{-\alpha_l\rho}. \tag{13}$$

Consequently, the solution of the coupling factor can be found by solving the following Euler-Lagrange equation,

$$\frac{\partial F}{\partial u} - \frac{d}{d\rho}\left(\frac{\partial F}{\partial u'}\right) = 0 \tag{14}$$

and that is:

$$\alpha_r(\rho) = \frac{2\alpha_l^2\rho}{1+2\alpha_l\rho-\exp\{2\alpha_l(\rho-R_{\max})\}(1+2\alpha_l R_{\max})} \tag{15}$$

Substituting (15) in (8), we have a tapered aperture field distribution which embodies an *early radiation* to cope with the power dissipation by the lossy waveguide. Without further mathematical complication, the coupling factor to realize uniform aperture field distribution in the lossy cases can also be derived by solving (8) with the *uniform* condition of the amplitude $E(\rho)$.

$$\alpha_r(\rho) = \frac{2\alpha_l^2\rho}{1-2\alpha_l\rho+\exp\{2\alpha_l(R_{\max}-\rho)\}(2\alpha_l R_{\max}-1)} \tag{16}$$

To avoid ambiguity, we define the coupling factor given by (15) as "*maximum gain coupling*" and (16) as "*maximum directivity coupling*".

By taking the limit of $\alpha_l \to 0$ in (15) and (16), we recover "*no loss design coupling*" $\alpha_r(\rho)$ as given in (4).

$$\lim_{\alpha_l\to 0}\alpha_r(\rho) = \frac{\rho}{R_{\max}^2 - \rho^2} \tag{17}$$

It should be noted that in the process of arriving at (15) and (16), the residual power t is neglected for simplicity. This neglect is quite acceptable for practical RLSA with the medium or higher gain since most of the power would be radiated by slots and further absorbed by lossy dielectrics before reaching the antenna rim.

3. Numerical Results

Some numerical examples are presented here to demonstrate the improvements of designs using the newly derived coupling factor given in (15) for lossy cases. At 60 GHz, a 400 mm (=80λ_0) diameter RLSA is analyzed for a lossy case with the loss factor α_l = 0.105 dB/mm.

Figure 4 compares the coupling distributions given by (4), (15), and (16). The maximum coupling factor $\alpha_{\max}$ is properly chosen as not to disturb the rotational symmetry of the inner field of RLSA [18]. It can be observed that, the *maximum gain coupling* (15) is stronger than *no loss design coupling* (4) and *maximum directivity coupling* (16), and all three curves are converged to a limitation $\alpha_{\max}$ while the slots position approaches the antenna rim. On the other hand, a *maximum directivity coupling* (16) is the weakest among these three.

The relationship between slot coupling and slot length is established by applying the Method of Moments (MoM) for a unit slot pair model with the periodic boundary condition [19]. Figure 5 presents the slot length distributions associated with the coupling factor distributions $\alpha_r(\rho)$ in Fig. 4. As results of strong coupled slots in maximum gain design, longer slots are adopted in the inner part of the aperture, and the curves are converged to a resonant length $SL_{\max}$ associated with the maximum coupling factor $\alpha_{\max}$ as the slots are positioned near the antenna rim.

The amplitudes corresponding to the couplings in Fig. 4 are then calculated by (8) together with (6), assuming the loss factor α_l = 0.105 dB/mm, and their normalized distributions are plotted in Fig. 6. The amplitudes corresponding to *maximum gain coupling* (15) and *no loss design coupling* (4) are both linearly tapered, and the sooner start at higher level than the latter one as a result of adopting stronger coupled slots in the inner part of the aperture. This steep tapered distribution confirms our desired *early radiation* as proposed in Fig. 3(b). Moreover, a uniform field corresponding to the *maximum directivity coupling* distribution consolidates the fidelity of (16) as well as the accuracy of our mathematical calculations in Sect. 2. Nonetheless, the low magnitude level (−11 dB) is the consequence of the excessively suppressed coupling to realize the uniformity against the existence of a considerable loss, and it suggests the gain degradation. We also include a uniform amplitude distribution normalized at 0 dB level for the lossless case (black line) as reference.

Finally, we calculate the antenna gain using (7) for a number of cases with different antenna sizes, loss factors, and coupling distributions, and plot it in Fig. 7. The antenna radius $R_{\max}$ is varied from 10λ_0 to 40λ_0 by a 10λ_0 step, and the loss factors α_l = 0, 0.06, or 0.105 dB/mm is considered here. Three designs corresponding to *maximum gain coupling* (15), *maximum directivity coupling* (16), and

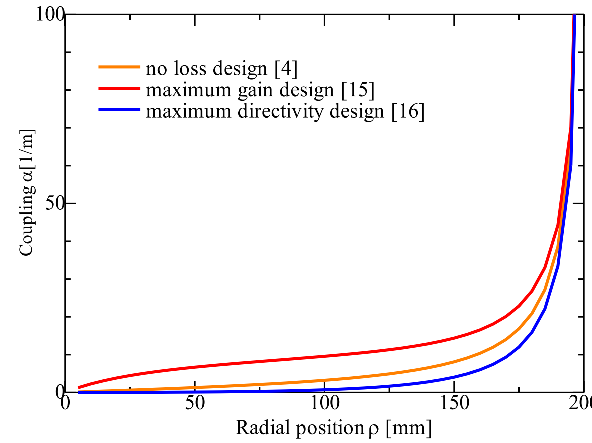

Fig. 4 Slot coupling distributions for loss factor α_l = 0.105 dB/mm and different coupling distributions.

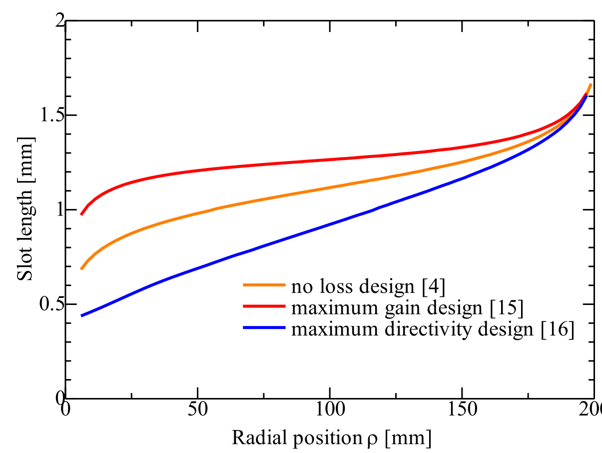

Fig. 5 Slot length distributions correspond to the slot coupling distribution in Fig. 4.

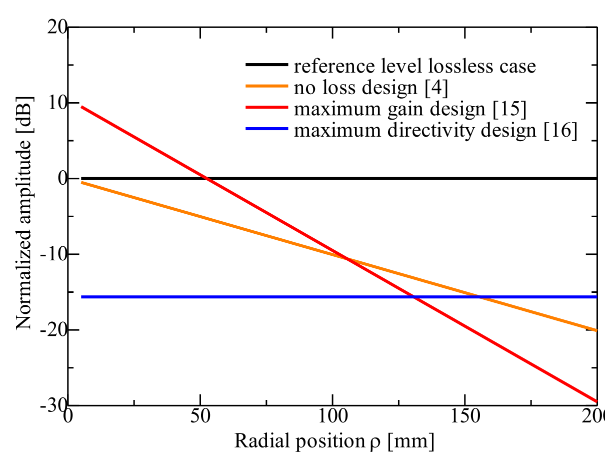

Fig. 6 Normalized amplitude distributions correspond to different coupling factor distributions.

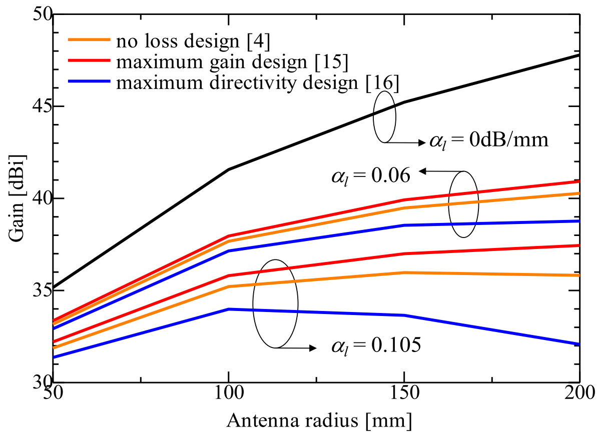

Fig. 7 Predicted gain for different antenna sizes and loss factors of the dielectric materials.

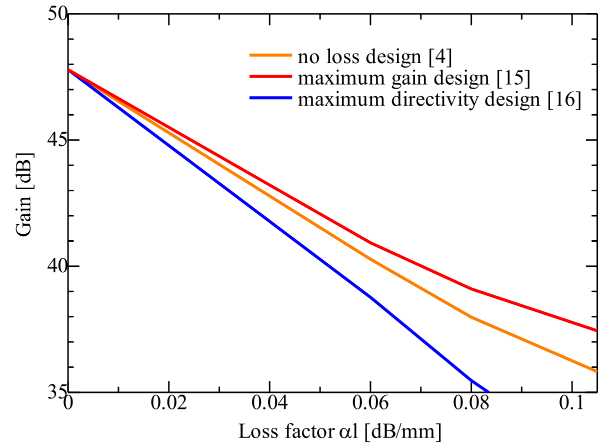

Fig. 8 Predicted gain for a ϕ = 400 mm antenna with different loss factors of the dielectric materials and different coupling distributions.

no loss design coupling (4) are distinguished by color, i.e., red, blue, and dark yellow, respectively. For the lossless case (α_l = 0 dB/mm), these lines are identical and indicated by the black line, as explained by (17).

Figure 7 suggests that loss factor α_l is the dominant parameter for the antenna gain though the new design (15) suppresses the degradation especially for larger radius and higher loss. For example, in case the loss factor α_l = 0.06 dB/mm and antenna radius R= 200 mm), more than about 7 dB gain degradation occurs. For lossy cases, the improvements of the red lines over the blue and dark yellow lines substantiate our idea, i.e., *early radiation* would prevent the dissipated power in lossy waveguides, hence increase the antenna gain. More importantly, the gain enhancement seriously depends on the loss factor and the antenna size, and is significant if the loss factor is very high (e.g., α_l = 0.105 dB/mm) and the antenna size is sufficiently large. For instant, a remarkable gain enhancement (≈1.5 dB) is achieved for $R_{\max}$ = 200 mm and α_l = 0.105 dB/mm.

From another view point, if the gain of 37 dBi is specified with the lossy material of α_l = 0.105 dB/mm, for example, only the *maximum gain design* (15) satisfies it by about 300 mm ϕ RLSA, while other design could not meet this specification even if the aperture size increases.

Figure 8 clarifies the advantage of the *maximum gain coupling* (15) over the *no loss design coupling* (4) and the *maximum directivity coupling* (16), by characterizing the gain of a 400 mm diameter RLSA as functions of the loss factor. Two observations can be drawn from this figure:

- the *maximum directivity design* suffers from the dielectric losses most seriously;
- the *maximum gain design* is indispensable to minimize the degradation caused by the dielectric losses, especially in case of very lossy dielectric materials and/or very large apertures.

4. Designs and Measurements of 60 GHz RLSAs Having Waveguides Filled with RO4003C™

In order to verify our theory proposed in Sect. 2 and confirm the numerical results calculated in Sect. 3, we designed and fabricated three 60 GHz RLSAs having 400 mm diameter and waveguides filled with a lossy material — Roger4003C (RO4003C™), a product of Rogers Corporation. RO4003C™ belongs to RO4000® series high frequency circuit materials, which provide stable electrical characteristics (dielectric constant ε_r, loss tangent δ) over a wide range in high frequency bands. Detail of RO4003C™ electrical properties are reported in RO4000® Laminates data sheet for 0.5 GHz up to 10 GHz band [20].

4.1 RO4003C™ Characteristics at 60 GHz by Outward Travelling Wave Measurement in a Radial Line

As the first step to prepare for the antenna design, we characterize the RO4003C™ at 60 GHz by outward travelling wave measurement in a radial line using our inner field measurement system. Operating mechanism of the inner field measurement system was explained in one of our recent reports [14]. This system provide us the one dimensional amplitude distribution of the field propagating inside RO4003C™ and the phase constant β, from which we can obtain the loss factor α_l and the dielectric constant ε_r, respectively.

Figure 9 presents the measured phase of the inner field. The gradient between measured curves and vertical axis defines the phase constant β, and it is from −132.7 deg/mm to −134.7 deg/mm. Substitute β into (18),

$$\varepsilon_r = \left(\frac{\lambda_0}{\lambda_g}\right)^2 = \left(\frac{\lambda_0\beta}{2\pi}\right)^2 \tag{18}$$

we can identify the dielectric constant ε_r of RO4003C™, as about 3.38∼3.5.

On the other hand, the measured amplitude of the inner

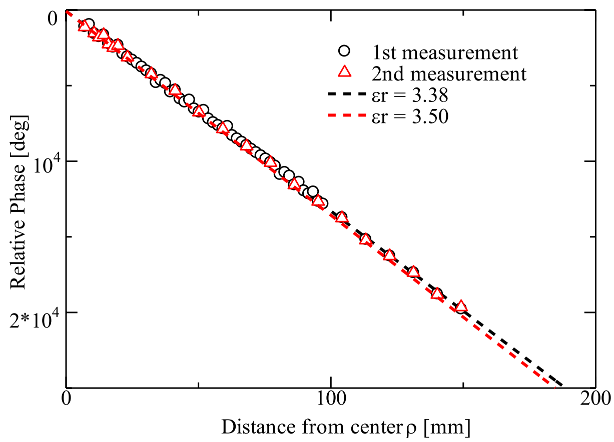

Fig. 9 Measured phase of the inner field in a radial-ρ direction.

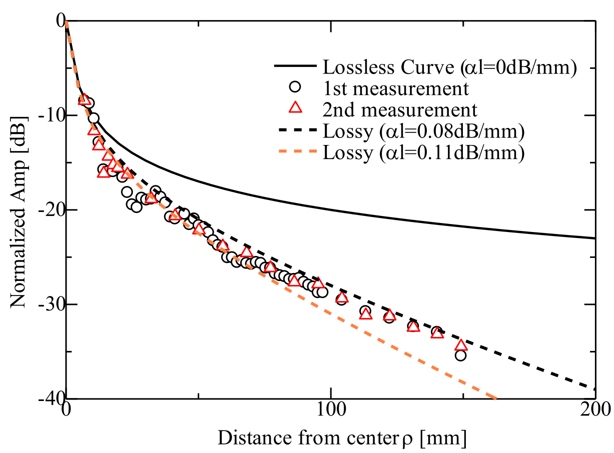

Fig. 10 Measured amplitude of the inner field in a radial-ρ direction.

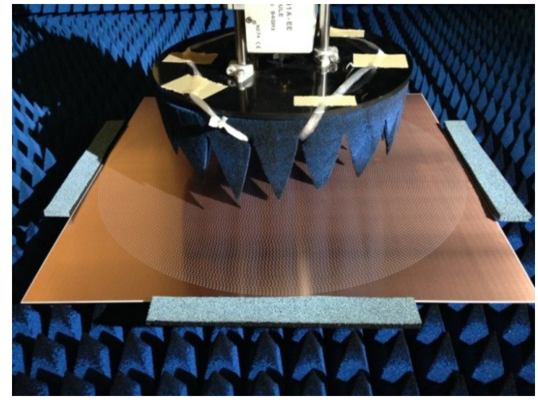

Fig. 11 A 400 mm RLSA prototype in Near Field Measurement.

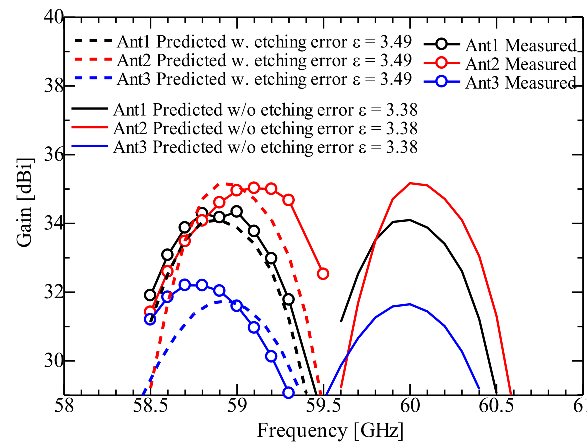

Fig. 12 Slot length distributions of two fabricated 900 mm prototypes.

field is indicated by the dotted lines in Fig. 10. There are some discrepancies at a radial distance of about 25 cm due to the standing wave operation, but in general, we can observe a decaying trend of the measured amplitude in comparison with the theoretical lossless curve of the cylindrical wave (solid black line). And from that, the attenuation or loss factor α_l is estimated to be about 0.08 dB/mm~0.11 dB/mm.

4.2 Designs and Measurements of 400 mm ϕ RLSAs

Three 400 mm diameter RLSAs were designed at 60 GHz with the coupling factor distributed as in (4), (15), and (16), and with the assumptions of the dielectric constant ε_r and loss factor α_l of RO4003C^{TM} are 3.38 and 0.105 dB/mm, respectively. Each antenna has more than 30000 radiating elements, and the fast design/ analysis procedure utilizing the Method of Moments (MoM) [13] is applied to predict the antenna performance. For clarification and simplicity, we name the antenna designed following the coupling factor distributed in (4), (15), and (16) as Ant1, Ant2, and Ant3, respectively.

Three antennas were designed at 60 GHz, and fabricated antennas were measured in the near field, with $5\lambda_0$ distance from the WR15 probe, as shown in Fig. 11. The measured gains of three RLSAs are indicated by the solid-dotted lines in Fig. 12. It is observed that the operating frequency of the three is shifted down by about 1 GHz from the prediction (solid lines). This frequency shift corresponds to the slot over-etching by about 27 μm, as is usual the case with slot fabrications at 60 GHz band [21], [22]. Regardless of the frequency shift, we confirm that Ant2, the design following the *maximum gain coupling* (15) has the best gain performance among these three prototypes; its peak is 0.8 dB and 3.2 dB higher than that of Ant1 — the *no loss design coupling* (4), and Ant3 — the *maximum directivity coupling* (16), respectively.

The predicted gain for three antennas using the parameters of over etching of 27 μm, slightly higher dielectric constant ε_r of 3.49 and the loss factor of 0.105, are also included in Fig. 12 by the dash lines, which reasonably agree with the measured gains of three antennas. These parameters are in range of the measurement sensitivity of RO4003C^{TM}, as explained in Fig. 9 and Fig. 10. This result substantiates our theory in Sect. 2, i.e. the *maximum gain coupling* proposed in (15) give us the best antenna performance in case high loss materials are used.

5. Conclusions

In this paper, we have proposed a new design concept for RLSAs having lossy dielectric substrates. Based on the operation of conventional RLSA, a mathematical formula of the new coupling factor was derived in order to maximize the antenna gain. Numerical results were presented to substantiate the accuracy of the new coupling factor for both lossless and lossy cases. Finally, three designs using high loss dielectric material — RO4003C^{TM}, and following different coupling factor distributions, were evaluated and their measurement results supported our new design concept. This *early radiation* design ideology can be applied to improve the performance of *Hayabusa 2* RLSA [14], which adopts high loss material-NoMEX® for the honeycomb structure.

Acknowledgments

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Tung Nguyen was born in Haiphong, Vietnam, on March 10, 1987. He received the M.S. degree in electrical electronic engineering from Tokyo Institute of Technology, Japan in 2012. From 2008 to 2009, he joined the Young Science Exchange Program (YSEP), as a researcher at Tokyo Institute of Technology, where he is currently pursuing the M.S degree. His interest has been antenna measurements. Latest the design of high frequency array antennas and planar antennas are his interests. Mr. Nguyen is a Member of IEICE and a Student Member of IEEE. He won the Student Paper Contest in ISAP2012, and a Best Paper Award in ICCE2014. In late 2014, he was named in the URSI Young Scientist Award Scheme.

Jiro Hirokawa was born in Tokyo, Japan, on May 8, 1965. He received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology (Tokyo Tech), Tokyo, Japan in 1988, 1990 and 1994, respectively. He was a Research Associate from 1990 to 1996, and is currently an Associate Professor at Tokyo Tech. From 1994 to 1995, he was with the antenna group of Chalmers University of Technology, Gothenburg, Sweden, as a Postdoctoral Fellow. His research area has been in slotted waveguide array antennas and millimeter-wave antennas. Prof. Hirokawa is a Fellow IEEE and IEICE. He received an IEEE AP-S Tokyo Chapter Young Engineer Award in 1991, a Young Engineer Award from IEICE in 1996, a Tokyo Tech Award for Challenging Research in 2003, a Young Scientists' Prize from the Minister of Education, Cultures, Sports, Science and Technology in Japan in 2005, a Best Paper Award in 2007, a Best Letter Award in 2009 from IEICE Communications Society and Asia Pacific Microwave Conference prize in 2011.

Makoto Ando received the D.E. degrees in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan in 1979. From 1979 to 1983, he worked at Yokosuka Electrical Communication Laboratory, NTT, and was engaged in development of antennas for satellite communication. He moved to Tokyo Institute of Technology in 1983 and is currently a Professor. His main interests have been high frequency diffraction theory such as Physical Optics and Geometrical Theory of Diffraction. His research also covers the design of waveguide planar arrays and millimeter-wave antennas. Prof. Ando is the Fellow IEEE and IEICE. He received the Achievement Award and the Paper Awards from IEICE Japan in 1993 and 2009. He also received the 8th Inoue Prize for Science in 1992, the Meritorious Award of the Minister of Internal Affairs and Communications and the Chairman of the Broad of ARIB in 2004 and the Award in Information Promotion Month 2006, the Minister of Internal Affairs and Communications. He served as the guest editor-in-chief of more than six special issues in IEICE, Radio Science and IEEE AP. He was the general chair of the 2004 URSI EMT symposium in Pisa and of the ISAP 2007 in Niigata. He was the Program Officer for engineering science group in Research Center for Science Systems, JSPS in 2006–2009. He served as the member of Scientific Council for Antenna Centre of Excellence - ACE in EU's 6'th framework programme since 2004. He served as the Chair of Commission B of URSI 2002-2005. He was the 2007 President of Electronics Society IEICE, the 2009 President of IEEE Antennas and Propagation Society and is currently the Co-chair of ISAP International Steering Committee and vice-president of URSI and IEICE.

Manuel Sierra Castañer was born in 1970 in Zaragoza (Spain). He obtained a degree in Telecommunication Engineering in 1994 and a Ph.D. in 2000, from the Technical University of Madrid (UPM) in Spain. He worked for Airtel, a cellular company, from 1995 to 1997. Since 1997, he worked in the University "Alfonso X" as an assistant professor. Since 1998 he has worked at the Technical University of Madrid as a research assistant, assistant professor and associate professor. He is a senior member of the IEEE. His current research interests involve planar antennas and antenna measurement systems. Dr. Sierra-Castañer obtained the IEEE APS 2007 Schelkunoff Prize for his paper "Dual-Polarization Dual-Coverage Reflectarray for Space Applications" in 2007.