Progress In Electromagnetics Research C, Vol. 45, 43–55, 2013

THE SQUARAX SPATIAL POWER COMBINER

Alberto Leggieri*, **Giancarlo Orengo, Davide Passi, and Franco Di Paolo**

Dipartimento di Ingegneria Elettronica, Università degli Studi di Roma "Tor Vergata", Via del Politecnico, 1-00133-Roma, Italia

Abstract—A broad-band transmission line spatial power combiner (SPC) is proposed in this paper, which uses a square coaxial (Squarax) transmission line (TL). This structure has some advantages over the traditional circular coaxial spatial power combiner, which have been described in this paper. Fin-Line to microstrip transitions are inserted into the Squarax TL, in order to allow an easy integration of Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifier (SSPA). The Squarax SPC geometry allows the feeding of a higher number of MMIC than in a Waveguide SPC, so that this structure ensures high power outputs and small sizes, together with theoretical DC frequency cut-off. In this work, the design and simulation of a passive 4–18 GHz Squarax SPC are reported.

1. INTRODUCTION

High power microwave amplifiers are typically based on travelling wave tube amplifiers (TWTAs), in order to provide high power levels which SSPAs cannot. However, instead of TWTAs, SSPAs need a short warm-up time, present a little standby mode power consumption and a less size [1]. This makes SSPAs the best candidate where high redundancy and device density are requested. The traditional approach to obtain a significant power output using SSPAs is the binary combining of many transistors through microstrip Transmission Lines [2, 3]. This solution is limited to the losses which each printed transmission-line combiner inserts. Binary combining, in addition, limits the number of devices to a power of two, and the designer may be forced to combine more than the necessary devices.

A complete different approach is the Spatial Power Combiner Amplifier [1, 4–10]. In this case, power dividing and combining is

Received 4 September 2013, Accepted 16 October 2013, Scheduled 21 October 2013
* Corresponding author: Alberto Leggieri (alberto.leggieri@uniroma2.it).

performed in a parallel way and losses are rather independent with the number of used PA's.

Compared to the binary combining, SPC approach offers several advantages, as high device compactness, low combining losses, higher available power outputs.

In this paper an innovative solution for SPC PA is shown. The proposed system is based on a Squarax TL and uses Fin-Line [11] to microstrip (FLuS) transitions to convert the energy of a square coaxial TEM fundamental mode to a microstrip quasi-TEM mode, which is then amplified by a SSPA. Many SSPAs outputs are recombined by the same principle.

In order to maximize the useful space for energy dividing and combining in the SPC, the Squarax TL configuration has been adopted. Since the FLuS cards can be placed all around the inner conductor of Squarax TL, a high number of such structures can be driven: this provide a high power output when MMIC PA's will be employed. In order to hold up the inner conductor of the Squarax several metal cards are used, each one holding FLuS transitions, as will be shown later.

A practical important aspect is the straightness of the Squarax SPC profile, which allows to be connected to a simple square or rectangular heat-sink devices, easily available in the market: it is completely different from the case of a Circular Coaxial SPC which needs apposite circular heat-sinker that require a custom production. Similarly, using a Circular Coaxial SPC there is the need of FLuS cards with a circular section of the lateral profile and with not planar faces, more expensive than simple rectangular cards as in the case of Squarax SPC.

Several circuital and technological solutions have been adopted. In order to reduce the combining loss and size, exponential FLuS transitions have been considered, using antipodal configuration.

In order to improve the operative band, a parasitic void has been implemented by inserting an anti-resonance metal in the antipodal FLuS transition profile [12].

In this work, the design and simulation of a 4–18 GHz Squarax SPC are shown. The simulation of the structure give an insertion loss of less than 2.5 dB using 16 cards, a gain variation of ± 0.5 dB and return loss better than 10 dB in the whole bandwidth.

This paper is organized as follows. In Section 2 the general concept of Spatial Power Combining will be revisited. In Section 3, the Squarax approach to the SPC is described, together with some mechanical CAD example of the final device. In Section 4, the theory and design of selected FLuS transition is described. In Section 5, the simulated result of 16 cards Squarax SPC are reported, together with the adopted simulation strategies. Finally, the Conclusions will summarize this work.

2. THE TRANSMISSION LINE SPATIAL COMBINING CONCEPT

In TL active SPC architecture each amplifier is connected to a probe, in order to couple its input port mode with the energy of the TL propagating mode. Several amplifiers, usually MMICs, are mounted in metallic cards containing their related functional circuitry, like probes, transitions, biasing: such cards are placed in parallel inside the TL. Input probes, printed on each card, receive a portion of the input power so that many lower amplitude signals are obtained, which are then amplified by PA's and routed to output probes. As much, these outputs are recombined coherently in an output TL by using the same principle, so the circuit consists of a back-to-back configuration of splitting and combining structure used as through elements.

In TL SPC architecture, the energy is distributed in low loss electromagnetic modes and combined in the TL dielectric, for example in a closed waveguide and, above all, using a single stage of power combining; this reduces the ohmic combining losses and makes it quite independent to the number of devices [9]: this general concept is shown in Figure 1.

The independent coupling of individual devices within the TL makes a little sensitivity to single-point failures, ensuring graceful degradation of output power. With a constant target output power,

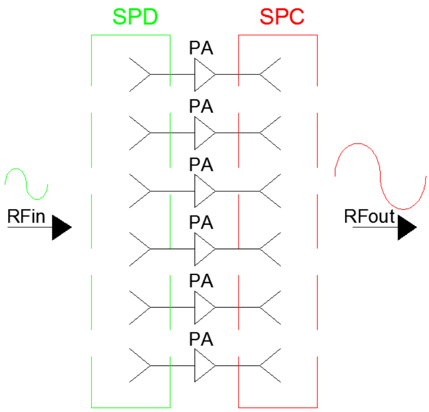

Figure 1. The general concept of SPC amplifier.

combining many devices by using the spatial approach allows to reduce size, weight, power draw, and cost. Since the loss is rather constant to the number of amplifiers, their size limits the combiner area with both the contributions of the active devices, the bias distribution and heat sink systems, which are especially important in order to avoid performance degradation and even device failure.

3. THE SQUARAX SPC SOLUTION

The Squarax TL is a coaxial line having square inner and outer conductors. Its cross section is described calling b the external side of the inner conductor and a the internal side of the outer conductor [15]. In order to maximize the useful space of mode combining of the SPC, the same FLuS structures can be implemented to couple a quasi TEM mode driven by a microstrip to a portion of the TEM mode of the Squarax. Circular Coaxial Transmission Lines (CCTL's) have been used extensively in the past, but square coaxial lines may be preferable since the presence of flat rather than circular surfaces offers mechanical advantages [13].

The Squarax SPC Amplifier proposed in this work is represented in Figure 2.

This Squarax used in this SPC is composed of three parts: the input and output parts, which are identical, make a transition from the input and output connector, a "N" type in the actual case, to the central part of the Squarax, which holds the FLuS transitions. The

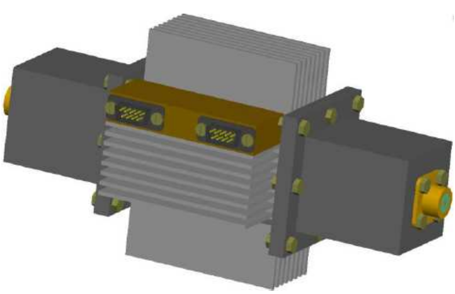

Figure 2. The proposed Squarax SPC amplifier completely assembled.

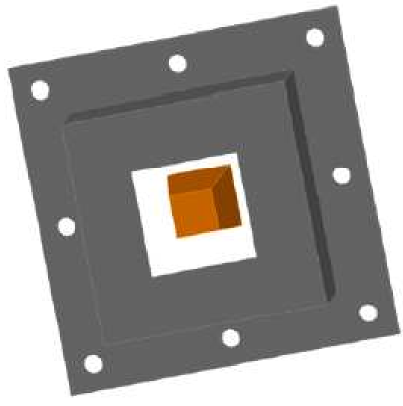

Figure 3. The terminal part of Squarax SPC: "N" connector is not represented for simplicity.

biasing of MMICs and control of the whole unit is made through a dedicated board, shown in brown color in Figure 2.

The input and output parts of the SPC will be simply referenced as "terminal" parts: they consist of a tapered Squarax transmission line, needed to match the 50 Ω source and load to the central part of the SPC: a terminal part is shown in Figure 3.

The central part of the Squarax SPC has no tapering, and it holds the FLuS transitions: the case with 16 cards is represented in a simplified view in Figure 4.

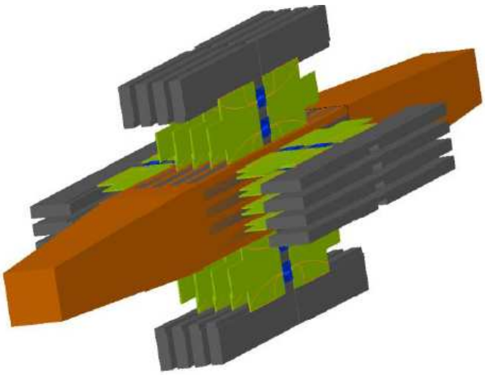

Figure 4. 16 carriers, each with two FLuS's, inside the central part of the Squarax SPC.

More cards can be inserted by proper impedance matching between the central section and the input/outputs ports.

Each cards is composed with input and output dual FLuS transitions, two MMICs, together with their bias circuitry, and a carrier holding all these components. The carrier is made with copper, to assure high thermal conductivity, and an interface sheet composed with CuMo compound, is placed under the MMIC to assure thermo-mechanical compatibility between GaAs MMIC and the carrier. A picture of the carrier is reported in Figure 5.

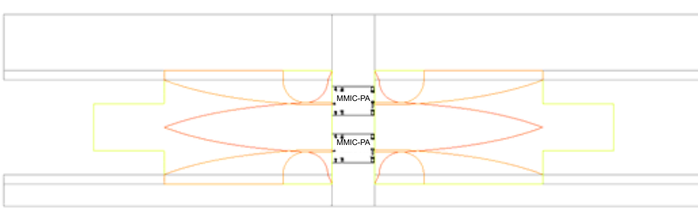

Figure 5. The carrier, holding FLuS's and two MMIC-PA's.

In the actual case, FLuS uses the rigid Al_2O_3 substrate, brazed on Cu carrier. The square profile of the Squarax determines the defined plane of polarization and the wave can travel down to the FLuS transitions to coherently couple their energy to the microstrips. Since such transitions can be placed all around the inner conductor of the Squarax, a higher number of FLuS transitions can be illuminated than in other TL, for example a rectangular WG [1, 8, 10]. Therefore, a high power output can be reached, because the power output of a SPC amplifier increases with the number of its internal coupled active devices.

Due to the straightness of its profile, the Squarax SPC can be connected to a simple square or rectangular heat-sink devices, which is easily available with a low cost. A classical circular CCTL needs a heat-sink with a semicircular cross section which has to be specially designed, requiring higher cost.

Moreover, when using a CCTL as a SPC, cards with a circular section of the lateral profile of the substrate are required; this further increases the manufacturing costs.

In a Squarax TL, in addition to the TEM fundamental mode, higher order modes can propagate. The higher order mode spectrum of circular coaxial lines is very well known [13]. As explained below, a Squarax TL can be used alternatively to a CCTL with its technological advantages, maintaining great wave-guiding properties as for the CCTL.

A method for the determination of the lowest (TE_{10} or TE_{01}) eigenvalues of transmission lines having square inner and outer conductors has been performed by Gruner [13]. As described there, the TE_{10} mode is the dominant higher order mode which may propagate in addition to the TEM mode. The degeneracy of the TE_{01} and TE_{10} modes is preserved in the sense that the dependence of their cutoff wavelengths on the aspect ratio b/a is the same; the field distribution of the TE_{01} mode is shifted by 90° relative to that of the TE_{10} mode, its form being otherwise identical. It can be noted that the cutoff wavelengths of the TE_{10} and the TE_{01} modes increase monotonically as the aspect ratio b/a is increased.

The outer and inner radii of the circular line are assumed to be equal to $2b/\pi$ and $2a/\pi$, respectively, thus making the mean circumferences of the corresponding square coaxial and circular coaxial lines the same and equal to $2(a + b)$ in both cases [13]. For low values of the index n, the characteristics of the $TE_{n,1}$ ($n = 0, 1, 2, \ldots$) modes in the square coaxial lines can be estimated by reference to the respective $TE_{n+1,1}$ modes of a circular coaxial line having the same mean circumference [13]. The Squarax TL normally has a constant ratio of the outer to inner conductors along the line of the tapered and uniform sections. The ratio was chosen to 3 : 1 so that the characteristic impedance of the line is as close as possible to the 50 Ω, that is, approximately 60 Ω or 63 Ω [14, 15].

Note the analytical characteristic impedance Z_c of the coaxial line of inner and outer square conductors of sizes $2a$ and $2b$ is given by (1):

$$\begin{aligned} Z_c &= 59.952 \cdot \ln(b/a) = 65.864\,\Omega \ \text{ or} \\ Z_c &= 376.62/[8a/(b-a) + 2.232] = 60.433\,\Omega, \end{aligned} \tag{1}$$

where $b/a = 3$ [14].

4. FLUS: FIN-LINE TO MICROSTRIP TRANSITION

The Squarax TL considered in this paper has a constant ratio b/a along its uniform section. In order to connect this TL to a coaxial connector, a tapered transition is used. From a standard coaxial connector, in this case a type "N" connector, a tapered Squarax section is required to adapt the smaller cross section near the connector to the larger cross section of the Squarax which contains the FLuS cards. However, the ratio varies continuously in the tapered section of the line. Subsequently, the characteristic impedance of the tapered section also varies. By choosing to 3 : 1 the ratio of the outer to inner conductor dimensions, the characteristic impedance of the SCTL line is approximately 61 Ω [14, 15].

A microstrip taper can be used as a broad-band impedance transformer between the tapered-slot antenna and MMIC amplifier, since the characteristic impedance at the taper end of the probe can be different to the impedance required by the PA input port matching condition. Therefore a portion of incident energy, being initially in TEM mode inside the Squarax, is efficiently converted into Fin-Line mode. Obviously the taper efficiency varies with its profile. The microstrip tapers have meandering shapes so that the taper lengths and the resulting phase differences remain the same among them.

4.1. Fin Taper Profile

In order to reduce the combining loss, the shape of the antenna taper has to be chosen properly so that return loss can be minimized within the frequency band of interest. Several spatial profiles of FL can be implemented: exponential, parabolic, sine, sine squared, cosine and cosine squared taper [11]. The former is chosen to ensure the smoothness of the taper, whereby very good matched-load is readily available for the Squarax, because this transition indeed reflects a small amount of incident power.

The spatial profile of an exponential Fin taper is given by (2):

$$w(z) = w_0 \exp\left[\frac{z}{l}\ln(w_f)\right] \tag{2}$$

where w_0 stands for initial taper width, and w_f for the final one. L is the total length of the transition [11]. The position dependent impedance of an exponential Fin taper is given by (3):

$$Z(z) = Z_0 \exp\left[\frac{z}{l}\ln\frac{Z_1}{Z_2}\right] \tag{3}$$

where Z_2 is the impedance to match, such as $61\,\Omega$ in the actual case, Z_1 the matching impedance, generally $50\,\Omega$, and z the coordinate of the longitudinal axis. By applying the small reflections theory, the spatial profile $w(z)$ can be taken as the uniform TL characteristic impedance $Z(z)$. From Riccati's equation it is possible to find the reflection coefficient trend [16] with respect the product βl, given by (4).

$$\Gamma = \frac{1}{2}e^{-j\beta l}\ln\left[\frac{Z_1}{Z_2}\frac{\sin(\beta l)}{\beta l}\right] \tag{4}$$

Microstrip Lines were designed following Hammerstad formulas reported in [17].

4.2. Antipodal Configuration

In order to obtain great system integration, antipodal configuration of Fin-Line to microstrip transition is an attractive solution [12], since transitions are in line with the direction of propagation and can be easily manufactured on inexpensive soft substrates or hard substrates, using standard printed circuit board techniques or sputtering techniques. This configuration expects two metal FL transition sheets placed among a dielectric substrate to lead hot and the ground planes. The profile of one sheet is the dual mirrored of the other.

In Figure 6 top metal sheets are in green, bottom ones are in yellow and the MMIC Amplifiers places are in blue.

4.3. Band Widening

The problem with using the antipodal configuration is the difficult to obtain broadband response, since the transition creates a set of resonant modes which limit its useful bandwidth [12]. Near the terminal microstrip section of Antipodal FLuS transition, where quasi

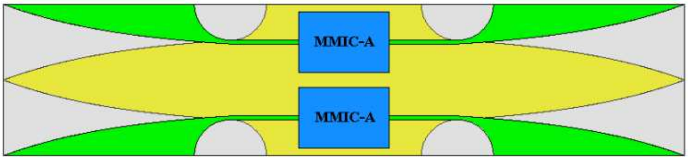

Figure 6. Fin line taper.

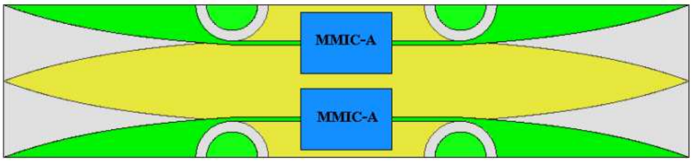

Figure 7. Fin line taper with resonance absorption.

TEM mode are being generated, TE_{10} mode tends to cutoff, and evanescent modes are being created, storing inductive energy. The Fin-Line discontinuity appears to the evanescent modes as a parasitic slot in a bisecting metal sheet. In this region electric field will be created, storing capacitive energy. When the capacitive energy created by the slot equals the inductive energy stored in the evanescent modes, a resonance will occur. In order to avoid this resonance, the Fin-Line discontinuities can be designed so as to break the slot electric field lines. An useful solutions has been applied; it consists to model a circular section through the metal sheet in the area where the parasitic slot might create, as shown in Figure 7. To improve the return loss, a dielectric Quarter Wave Transformer (QWT) may be provided. This device helps fields to adapt themselves to substrate load, in according to the small reflections theory.

5. DESIGN AND SIMULATIONS OF A 16 CARDS SQUARAX SPC

Return loss characteristic of the passive structure SPC depends also on the number of inserted cards. In order to meet the operating power goals with the fewest possible devices, to minimize the insertion loss and to maximize the return loss, the better configuration can be found selecting the profile shape of the FLuS (including the microstrip transformer and the anti-resonance circular section) which allows to accommodate the optimum number of cards and the number of devices per card to insert in the target Squarax.

A 16 cards Squarax SPC in the operative bandwidth 4–18 GHz has been designed, able to account for 32 MMIC SSPAs. The inner part has the cross sections $a = 13.524\,\mathrm{mm}$ $b = 33.524\,\mathrm{mm}$, while the tapered transition from coaxial input and output sections to the inner part is 60 mm long. Exponential tapered FL transitions are mounted on 16 cards placed at each side of the Squarax. The FLuS are made on Al_2O_3 substrate, with a thickness of 0.254 mm. Each card contains two FLuS connected back to back with double asymmetrical QWT sections. The Squarax conductors have been considered as copper, which has excellent thermal conductivity.

Simulation of the proposed device has been performed, using HFSS version 15 of Ansys-Ansoft. The 3D simulated structure is shown in Figure 8.

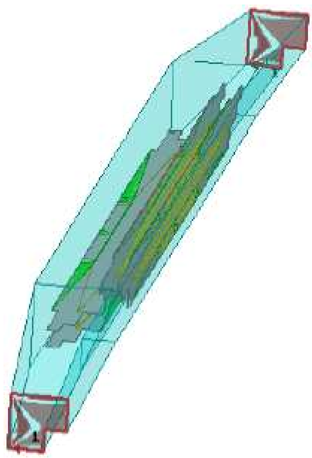

Figure 8. The simulated 3D quarter section of the Squarax SPC.

The simulated S-parameters are given in Figures 9, s_{11}, and 10, s_{21}.

We note that the Squarax SPC ensures a maximum insertion loss of 2.3 dB and a minimum Return Loss of 10 dB in the whole 4–18 GHz.

Several problems were solved, such as a large amount of tetrahedra in meshing steps and several resonance occurrences. At last about 980 thousands tetrahedra versus 8 millions ones have been obtained, resulting in a reliable modeling which has ensured correct results. This improvement was achieved by defining two Perfect Magnetic Conductors (PMC) within the Squarax SPC. Furthermore, since a good discretization of the Fin taper profile was of fundamental

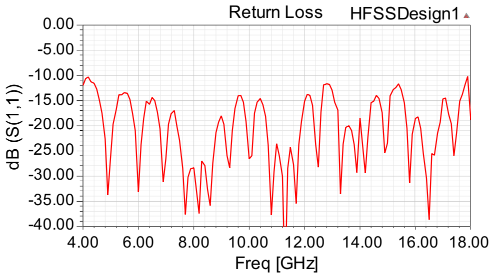

Figure 9. Simulated reflection coefficient, in dB, of the Squarax SPC.

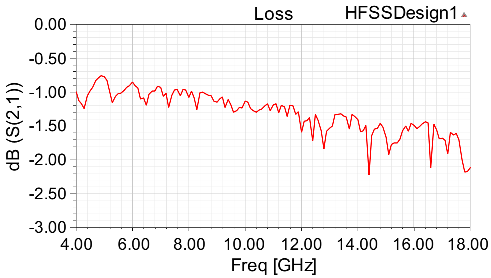

Figure 10. Simulated transmission coefficient, in dB, of the Squarax SPC.

importance, the exponential profile was approximated with a discrete number of points such that the different segment obtained were smaller than $\lambda/20$ at the highest frequency of the operative band. In this way the discretization doesn't affect the performance but reduces the computational complexity.

By adopting these strategies and by enabling the Iterative Solver implemented in HFSS Release 15, 9.7 GB of memory have been employed, instead of 32 GB ones necessary without this reduction.

A dimensioning optimization of the Squarax SPC length has been needed to cut out the resonances.

In order to improve the lower band return loss and to extend the operative bandwidth, a longer FLuS can be used, with a negligible insertion loss degradation. A group QWT's, tuned to different frequencies from the actual, can be a preferable solution. A triple QWT's may be also designed.

A next 32 cards Squarax SPC can be designed, able to account 64 MMIC SSPAs in order nearly to double the available power output.

6. CONCLUSIONS

The Squarax SPC technology has been studied and several circuital and technological solutions have been adopted. The Squarax SPC represents an innovative solution, in order to increase available power outputs and low cost.

By using this solution, optimal results have been achieved. A Squarax SPC has been designed with great performance: the model presents gain variation of $\pm 0.4\,\mathrm{dB}$, and $10\,\mathrm{dB}$ minimum for Return Loss for the whole 4–18 GHz. The structure offers 14 GHz of Operative Band with about $230\,\mathrm{cm}^3$ of volume.

REFERENCES

1. Than, H. T., G. W. Sun, G. S. Cuellar, J. Y. Zeng, N. T. Schultz, M. E. Moya, Y. Chung, B. C. Deckman, and M. P. DeLisio, "Design and performance of a 600-W-band amplifier using spatially combined GaAs FETs for satellite communications," *IEEE Journal of Solid-State Circuits*, Vol. 47, No. 10, Oct. 2012.
2. Russel, K. J., "Microwave power combining techniques," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 27, No. 5, 472–478, May 1979.
3. Chang, K. and C. Sun, "Millimeter-wave power combining techniques," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 31, No. 2, 91–107, Feb. 1983.
4. Courtney, P. G., T. Tran, C. Bartak, S. Behan, and P. Jia, "High efficiency 80 W X-band power amplifier using coaxial waveguide spatial power combining technique," *International Microwave Symposium Digest*, 1396–1399, Anaheim, CA, USA, May 23–28, 2010.
5. Russo, I., L. Boccia, G. Amendola, and G. Di Massa, "Parametric analysis of grid amplifiers," *Proceedings of European Microwave Week 2008*, 1326–1329, Amsterdam, 2008.
6. An, D., X. Li, J. Mou, and X. Liv, "A new type of Ka-band waveguide-based power combining structures," *Proceedings of ICMMT 2008*, 1–4, Nanjing, China, Apr. 21–24, 2008.
7. Russo, I., L. Boccia, G. Amendola, and H. Shumacher, "Compact hybrid coaxial architecture for 3–10 GHz UWB quasi-optical power combiner," *Progress In Electromagnetics Research*, Vol. 122, 77–92, 2012.
8. Lopz, D., L. Bortoli, J.-P. Fraysse, D. Langrez, J. F. Villemazet, J. L. Cazaux, G. Soubercaze-Pun, and L. Lapierre, "HPA module

for active antenna applications," *Proceedings of 5th European Microwave Integrated Circuit Conference*, 404–407, Paris, Sep. 27–28, 2010.
9. DeLisio, M. P. and R. A. York, "Quasi-optical and spatial power combining," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 3, Mar. 2002.
10. Cheng, N.-S., P. C. Jia, D. B. Rensch, and R. A. York, "A 120-W X-band spatially combined solid-state amplifier," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 12, Dec. 1999.
11. Bhat, B. and S. K. Koul, *Analysis, Design and Optimization of Fin Lines*, Artech House, 1987.
12. Ponchak, G. E. and A. N. Downey, "A new model for broadband waveguide to microstrip transition design," *NASA Technical Memorandum 88905*, Lewis Research Center Cleveland, Ohio, Dec. 1986.
13. Gruner, L., "Higher order modes in square coaxial lines," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 31, No. 9, Sep. 1983.
14. Kang, T.-W., C. Christopoulos, and J. Paul, "A square coaxial transmission line with a thin-wire inner conductor to measure the absorbing performance of electromagnetic absorbers," *Journal of the Korea Electromagnetic Engineering Society*, Vol. 4, No. 1, Mar. 2004, JKEES 2004-4-1-08.
15. Wadell, B. C., *Transmission Line Design Handbook*, Artech House, 1991, ISBN 0-89006-436-9.
16. Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, 1998, ISBN 0-471-44878-8.
17. Di Paolo, F., *Networks and Devices Using Planar Transmission Lines*, CRC Press LLC, 2000, ISBN 0-8493-1835-1.