Power-Recycling Feedback System for Maximization of Leaky-Wave Antennas' Radiation Efficiency

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***Abstract*—A novel power-recycling feedback scheme is proposed for systematic maximization of the generally poor radiation efficiency of leaky-wave antennas (LWAs). In this scheme, the nonradiated power at the end of the LWA structure, instead of being lost in the terminating load, is fed back to the input of the LWA through a power-combining system, which constructively adds the input and feedback powers while ensuring perfect matching and isolation of the two signals. As a result, the radiation efficiency of the isolated (or open-loop) LWA η_0 is enhanced by the system's gain factor G_s ($G_s > 1$) to the overall radiation efficiency of $\eta_s = G_s\eta_0$, which may reach 100% for any value of η_0 in a lossless system. The design of the power-recycling system depends on η_0, which typically results from a tradeoff between required directivity and restricted size. The paper derives, for a rat-race-based implementation, the exact design equations, which determine both the rat-race impedance ratios and the feedback phase conditions of the system. The build-up of the steady-state regime from the transient regime at the onset of the system is explicated by transient circuit and electromagnetic simulations. Finally, an experimental power-recycling LWA system, including naturally ohmic and dielectric losses in addition to other imperfections, is demonstrated, where the isolated antenna efficiency η_0 is enhanced from 38% to 68%, corresponding to a system efficiency enhancement of $G_s = 1.8$. The proposed power-recycling feedback system applies to all LWAs and solves their fundamental efficiency problem in practical applications involving a tradeoff between relatively high directivity (higher than half-wavelength resonant antennas) and small size (smaller than open-loop LWAs or complex phased arrays).**

***Index Terms*—Composite right-/left-handed (CRLH) structures, feedback, leaky-wave antenna (LWA), power-recycling, radiation efficiency, rat-race coupler.**

I. Introduction

LEAKY-WAVE antennas (LWAs) constitute a class of traveling-wave antennas that exhibit high directivity and frequency scanning capabilities, while requiring no complex feeding networks [1]. However, they generally suffer from low radiation efficiency, because all of the power that has not been radiated when reaching the end of the leaky-wave structure is dissipated in the matched load. For typical values of leakage factors, a radiation efficiency of 90% requires a structure length of the order of 8–10 λ_0 [1]. Such sizes are impractical in most microwave wireless systems.

Recently, the authors proposed a high-efficiency LWA array using a power-recycling series feeding network [2]. This antenna was a 2-D array, which recycled the power left at the output of the center element into the input of the neighboring elements and then further recycling the power left at the output of these neighbors into the next adjacent elements. Using this *cross-recycling* mechanism, the overall antenna with five elements reached a radiation efficiency of more than twice that of a single-antenna element. However, this approach for efficiency enhancement is applicable only to an array and not to a single LWA.

In this study, we present a novel power-recycling scheme that maximizes the radiation efficiency of any single LWA, by using a *self-recycling* mechanism, where the nonradiated power at the end of the structure is fed back into the input of the antenna itself. Such a power-recycling system may enhance the radiation efficiency of any LWA to 100% in a lossless system. Although a 100% efficiency cannot be achieved in a practical lossy system, the proposed mechanism provides a significant radiation efficiency enhancement.

A similar power-recycling technique was reported in an optical system for a gravitational-wave antenna in [3]. In this antenna, a partially transmitting mirror is used to recycle the light power back into the main interferometer in order to increase the effective power and hence enhance the power gain of the system. At microwaves, a LWA having its output connected back to its input, so as to form a self-oscillating antenna, was reported in [4], but this system, as an oscillator, does not have any input port and can therefore not transmit a modulated signal. Moreover, the amount of radiated power cannot be controlled, and no attempt was made to enhance the radiation efficiency in this self-oscillating antenna.

Thus, the proposed power-recycling LWA system constitutes a unique solution for efficiency enhancement of LWAs. Using this system, a LWA may provide an optimal solution for applications where a tradeoff between directivity and size exists, more specifically, when a directivity higher than that of resonant antennas is required but where size is restricted to much less than the huge sizes of 8–10 λ_0 mentioned above. For instance, an LWA of the length of the order of 1–3 λ_0 may exhibit a directivity and gain significantly larger than that of a $\lambda_0/2$ resonant antenna, while avoiding the complexity of a conventional antenna array.

This paper considers only the case of fixed broadside radiation, where the main benefit of the power-recycling system is radiation efficiency enhancement. However, the structure may be

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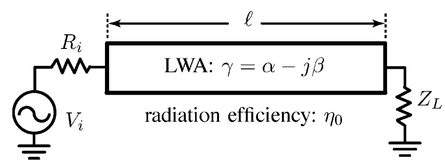


Fig. 1. Schematic of a conventional LWA terminated with a matched load Z_L.

refined and incorporate real-time tuning phase shifters in order to also provide beam scanning.

This paper is organized as follows. Section II presents the principle of self power-recycling LWA. Section III proposes a rat-race-based system configuration and its theoretical demonstration. Section IV describes the transient operation of the system at the onset of the source in order to explicate how the fields build up into the steady-state regime. An experimental demonstration is made in Section V. Finally, conclusions are given in Section VI.

II. Principle of Feedback Power Recycling

Fig. 1 shows the schematic of a conventional LWA of length ℓ terminated with a matched load Z_L. This antenna has a propagation constant β and an attenuation constant α, which includes, in general, both leakage and ohmic/dielectric/mismatch loss. We consider here a harmonic excitation with voltage V_i. The input wave propagates along the LWA structure and, when it is faster than light (i.e., at frequencies where $\beta < k_0$), it progressively leaks out to the free space to build up a radiating beam at the angle $\theta = \sin^{-1}(\beta/k_0)$. The remaining power at the end of the LWA is absorbed by the matched load Z_L and may be related to the input power P_i as $P_L = P_i e^{-2\alpha\ell}$. Therefore, the radiation efficiency of the LWA reads [1]

$$\eta_0 = \frac{P_{\rm rad}}{P_i} = \frac{P_i - P_L - P_{\rm loss}}{P_i} = 1 - e^{-2\alpha\ell} \tag{1}$$

where a lossless structure has been assumed in the second equality, i.e., $P_{\rm loss} = 0$, for the sake of simplicity, without loss of generality. In this case, the attenuation constant α is solely due to leakage and reduces exactly to the leakage factor.

According to (1), in order to increase the radiation efficiency of an LWA to a maximum level, one needs to increase its length until almost all of the input power (typically 90% [1]) has been radiated. This results in enhanced directivity, due to increased radiation aperture, but may also imply an excessively large size, which is generally prohibitive toward low frequencies. Consequently, LWAs are typically designed with lengths for which a substantial fraction of the input power reaches its output and is lost in the load, leading to a low radiation efficiency.

Fig. 2 shows the proposed power-recycling LWA system, which provides a remedy to this fundamental efficiency problem, by recycling the nonradiated power at the end of the antenna back into its input. This system incorporates an ideal adder in a feedback loop of the LWA, which sums the

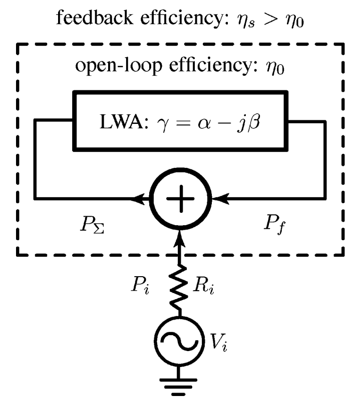


Fig. 2. Proposed power-recycling LWA system.

applied input and recycled signals. The resulting signal that appears at the input of the LWA has a larger amplitude than the applied input signal for a nonzero recycled signal. As a result, the radiated power of the power-recycling LWA system is increased compared with the case of the open-loop LWA, and hence the radiation efficiency η_s of the feedback system is superior to that of the open-loop (isolated) LWA $\eta_s > \eta_0$.

The adder in Fig. 2 may be realized by a Wilkinson combiner (a three-port network) or by a 180° hybrid coupler (a four-port network) in the form of a rat-race, a tapered coupled-line coupler, or a magic-T [5]. As will be seen in Section III, the adder will need to accommodate different power-combining ratios depending on the open-loop LWA efficiency η_0. In the case of the Wilkinson combiner, this would require impedance transformers for matching to a system of impedance Z_0 at two output ports [5]. Therefore, the 180° hybrid option was preferred in this work. Specifically, we chose the rat-race, because the conventional magic-T is nonplanar and the tapered coupled-line coupler is harder to design and suffers from limited coupling levels.

III. System Configuration and Theoretical Demonstration

Here, we demonstrate and characterize the rat-race-based power-recycling system using a scattering parameter approach, first for an LWA of arbitrary radiation efficiency η_0 and then specifically for the case of a 3-dB LWA system, corresponding to an LWA efficiency of $\eta_0 = 0.5$.

A. Rat-Race System Implementation and Operation Principle

Fig. 3 shows the rat-race-based implementation of the power-recycling LWA system of Fig. 2, along with the port and wave voltage notations that will be used in this forthcoming analysis. Two transmission lines, ℓ_{45} and ℓ_{63}, have been added in the feedback loop to provide the proper phase condition for maximal system efficiency η_s. The difference port is terminated by a matched load Z_L.

In order to provide arbitrary power-combining ratios, the rat-race includes two sets of transmission-line sections, with respective impedances $Z_{0a} = Z_0/a$ and $Z_{0b} = Z_0/b$, as shown in Fig. 3, where a and b are positive real numbers satisfying the

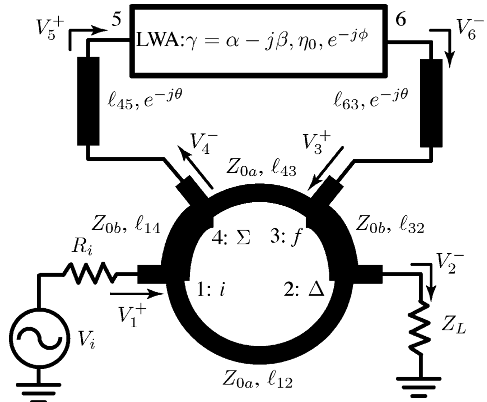


Fig. 3. Rat-race=based implementation of the power-recycling LWA system shown in Fig. 2. In general, the rat-race exhibits different power-combining ratios, corresponding to two sets of impedances (Z_{0a} and Z_{0b}), depending on the open-loop efficiency η_0 of the LWA. Notation for the 180° hybrid ports: i: input; f: feedback; Σ: sum; Δ: difference.

relation $a^2 + b^2 = 1$ for perfect isolation between the two coupled ports (ports 1 and 3) [6]. The resulting scattering matrix [S] reads

$$\begin{bmatrix} V_1^- \\ V_2^- \\ V_3^- \\ V_4^- \end{bmatrix} = \begin{bmatrix} 0 & ja & 0 & -jb \\ ja & 0 & -jb & 0 \\ 0 & -jb & 0 & -ja \\ -jb & 0 & -ja & 0 \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ V_3^+ \\ V_4^+ \end{bmatrix} \tag{2}$$

where V_i^+ and V_i^-, $i = 1, 2, 3, 4$, represent the incident and reflected voltages of port i, respectively.

The power-recycling LWA system operates as follows. The rat-race coupler constructively adds the input (i, port 1) and recycled or feedback (f, port 3) signals at its sum port (Σ, port 4), toward the input of the LWA, while using its difference port (Δ, port 2) for matching in the steady-state regime and for power regulation in the transient regime, as will be shown later. In addition, it provides perfect isolation between the input and feedback ports, which ensures complete decoupling between the corresponding signals. Via this *positive* (i.e., *additive*) feedback mechanism, the power appearing at the input of the LWA progressively increases during the transient regime until it reaches its steady-state level, leading to a theoretical system radiation efficiency of 100%, as will be demonstrated next.

B. Demonstration of Efficiency Enhancement

Throughout this section, we consider again, without loss of generality, the case of a lossless system (no ohmic, dielectric, or mismatch losses). The actual losses will be automatically taken into account and will be discussed in the experimental demonstration (Section V). It will be shown that, in such a lossless system, the efficiency η_s of the system can be enhanced to 100%. Essentially, assuming that the rat-race within the system is matched at the input (source) port, this will be achieved when the rat-race is designed so as to nullify the power at the difference (load) port, i.e., $V_2^- = 0$.

We may then write

$$V_2^- = S_{21}V_1^+ + S_{23}V_3^+ = 0. \tag{3}$$

This expression can be transformed as follows:

$$\begin{aligned} 0 &= S_{21}V_1^+ + S_{23}V_3^+ \\ &= S_{21}V_1^+ + S_{23}e^{-j2\theta}e^{-j\phi}\sqrt{1-\eta_0}V_4^- \\ &= S_{21}V_1^+ + S_{23}e^{-j(2\theta+\phi)}\sqrt{1-\eta_0}(S_{41}V_1^+ + S_{43}V_3^+). \end{aligned} \tag{4}$$

In the last expression, V_3^+ may be expressed as a function of V_1^+ using (3), i.e., $V_3^+ = -S_{21}/S_{23}V_1^+$, which, with $V_1^+ \neq 0$, yields

$$S_{21} + S_{23}e^{-j(2\theta+\phi)}\sqrt{1-\eta_0}\left(S_{41} - \frac{S_{21}}{S_{23}}S_{43}\right) = 0. \tag{5}$$

Substituting the scattering parameters of the rat-race, given by (2), into this relation yields

$$ja = \sqrt{1-\eta_0}e^{-j(2\theta+\phi)} \tag{6}$$

which finally provides the sought conditions for $\eta_s = 100\%$, taking into account the rat-race relation $a^2 + b^2 = 1$ as

$$a = \sqrt{1-\eta_0} \quad b = \sqrt{\eta_0} \tag{7a}$$

$$\theta = -\frac{\phi}{2} + \frac{3\pi}{4} + m\pi, \qquad m \in \mathbb{N}. \tag{7b}$$

Equation (7a) gives the impedances of the transmission-line sections building the rat-race, while (7b) gives the required length of the two transmission lines building the feedback loop (Fig. 3). Fig. 4(a) plots the values of a and b with respect to the open-loop LWA radiation efficiency η_0. When $\eta_0 = 0.5$, corresponding to 50% efficiency, $a = b = 1/\sqrt{2} = 0.707$, which corresponds to a 3-dB (equal power combining) rat-race. This particular case will be demonstrated by circuital, full-wave, and experimental results in the next two sections.

When the conditions of (7a) and (7b), which are the conditions for $V_2^- = 0$ [(3)], are met, the radiation efficiency of the power-recycling LWA system reads, following (1), as

$$\begin{aligned} \eta_s &= \frac{P_{\rm rad}}{P_i} \\ &= \frac{P_i - P_L}{P_i} \\ &= \frac{P_1 - P_2}{P_1} \\ &= 1 - \frac{P_2}{P_1} \\ &= 1 - \left(\frac{V_2^-}{V_1^+}\right)^2 \\ &= 1 - \left(\frac{0}{V_1^+}\right)^2 \\ &= 1 \quad \text{or} \quad 100\%. \end{aligned} \tag{8}$$

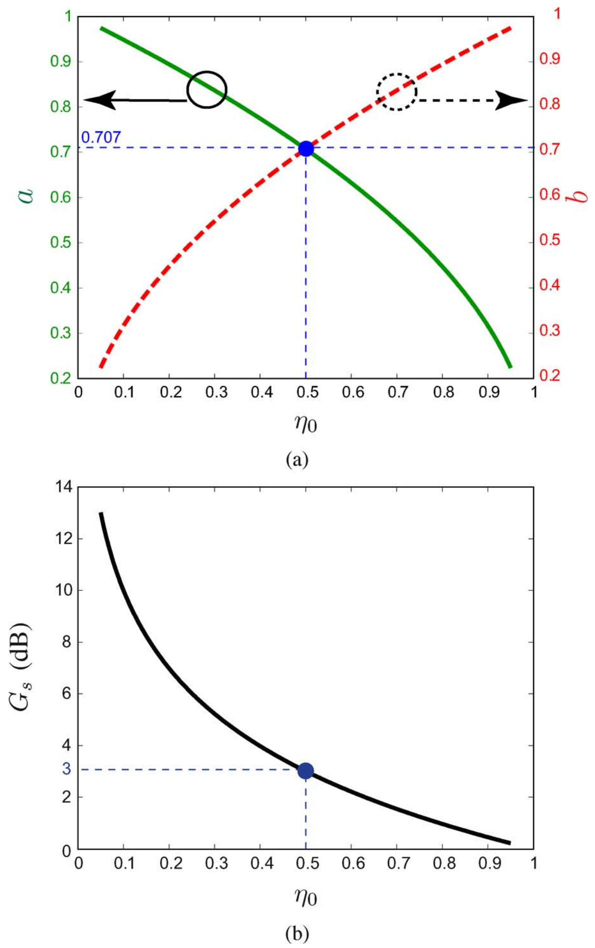


Fig. 4. Design and performance of the power-recycling system versus the open-loop (isolated) LWA radiation efficiency η_0 for 100% (lossless) LWA system efficiency ($\eta_s = 1$). (a) Normalized impedances a and b of the rat-race (see Fig. 3) computed by (7a). (b) Power-recycling gain G_s computed by (11).

It is useful to relate the radiation efficiency of the system to that of the open-loop LWA. For this purpose, we define here a system *power-recycling gain* G_s as $G_s = P_4/P_1$ or

$$\begin{aligned}\sqrt{G_s} &= \frac{V_4^-}{V_1^+} \\ &= \frac{S_{41}V_1^+ + S_{43}V_3^+}{V_1^+} \\ &= S_{41} + S_{43}\frac{V_3^+}{V_1^+} \\ &= S_{41} - S_{43}\frac{S_{21}}{S_{23}}. \end{aligned} \tag{9}$$

From this equation, the relation between η_s and η_0 is found to be

$$\begin{aligned}\eta_s &= \frac{P_{\rm rad}}{P_i} \\ &= \frac{P_{\rm rad}}{P_5}\frac{P_5}{P_4}\frac{P_4}{P_i} \\ &= \eta_0\left(\frac{V_5^+}{V_4^-}\right)^2\left(\frac{V_4^-}{V_1^+}\right)^2 \\ &= \eta_0 \cdot 1 \cdot G_s \\ &= \eta_0 G_s. \end{aligned} \tag{10}$$

The power-recycling gain can be expressed as a function of the open-loop and system efficiencies

$$G_s = \frac{\eta_s}{\eta_0} > 1 \tag{11}$$

which reduces to $G_s = 1/\eta_0$ for 100% system radiation efficiency. This relation expresses the fact that, to reach a given overall efficiency η_s, the system must provide a gain G_s inversely proportional to the open-loop LWA and exactly equal to η_s/η_0. In other words, as $\eta_s = G_s\eta_0$, the efficiency of the open-loop (isolated) LWA has been increased by a factor G_s in the power-recycling system. Equation (11) is plotted in Fig. 4(b) for $\eta_s = 1$.

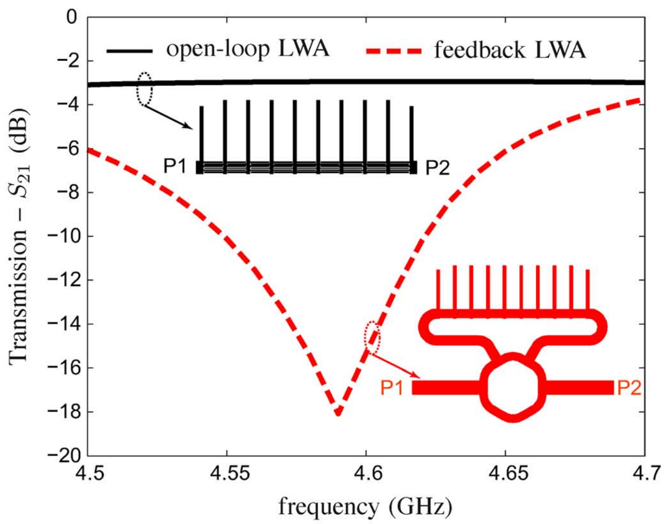
It may seem shocking at first glance that "gain" is produced by a purely passive system. However, this "gain" is not a gain in the sense of an active amplifier gain, where energy is added into the system by an external dc source, resulting in a system output power $P_{\rm out}$ larger than the input power $P_{\rm in}, P_{\rm out} = {\rm GP}_{\rm in} > P_{\rm in}$. Here, the role of the "external source" is played by the feedback loop, but this source is external only with respect to the rat-race, which effectively sees two power sources (ports 1 and 3). *From the viewpoint of the rat-race*, this leads to a larger power at the input of the LWA (P_Σ) compared with the power at the input of the system $(P_i), P_\Sigma = G_sP_i > P_i$, hence the analogy with an active system. However, no energy has been added to the *overall system*, and no more power is radiated than the power provided by the source.

C. Particular Case of a 3-dB Broadside System

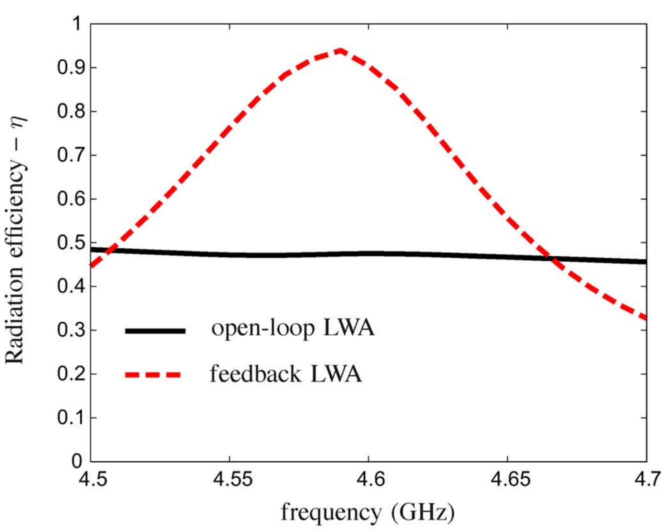
According to Fig. 4, the proposed power-recycling scheme can accommodate any open-loop LWA radiation efficiency. We will consider here the particular case of an open-loop efficiency of 50%, which corresponds to an average situation in practice and which is implemented here with a simple 3-dB rat-race coupler. Couplers with other power-division ratios may naturally be used for other efficiencies. For very low radiation efficiencies, the utilization of a rat-race coupler would be unpractical because, as shown in Fig. 4(a), this would correspond to excessive admittance ratios for the two sets of transmission lines constituting the rat-race coupler. In this case, a coupled-line coupler, easily achieving low coupling levels, is recommended instead. In the case of very high radiation efficiencies, very large admittance ratios would also be required, but in this case the power-recycling scheme itself loses its usefulness.

According to (7a), a 3-dB power-recycling LWA system corresponds to a 3-dB (equal power combining) rat-race, $a = b = 1/\sqrt{2}$, and an LWA having an open-loop radiation efficiency of 50% (i.e., $\eta_0 = 0.5$). In addition, we consider here the case of broadside radiation, which corresponds to $\phi = 0$ in (7b). In order to demonstrate the radiation efficiency enhancement in a practical real implementation, an open-loop LWA and a 3-dB power-recycling system were designed and simulated using the Method of Moments (Ansoft Designer).

Fig. 5(a) shows the transmission parameter S_{21} of both the open-loop LWA and the power-recycling LWA system. The



(a)



(b)

Fig. 5. Full-wave (method of moments, Ansoft Designer) demonstration of a 3-dB power-recycling LWA system designed at 4.58 GHz in the lossless case (neither ohmic nor dielectric losses), comparing the open-loop LWA (Fig. 1) and the power-recycling LWA (Fig. 3). The LWA is an interdigital/stub CRLH LWA [7] with the parameters: number of unit cells: $N = 10$; unit cell length: $p = 208$ mil; number of fingers: $N_f = 6$ (three pairs); finger width: $w = 15$ mil; inter-finger gap: $g = 6$ mil (everywhere); stub width: $w_{\mathrm{stub},1} = 39$ mil; length of first and last stubs: $L_{\mathrm{stub},2} = 580$ mil; length of other stubs: $L_{\mathrm{stub}} = 644$ mil; substrate thickness: $h = 62$ mil; substrate permittivity: $\varepsilon_r = 2.2$. (a) S-parameters. (b) Radiation efficiency.

antenna is an interdigital/stub composite right-/left-handed (CRLH) LWA [7] with the design parameters given in the caption of the figure. The transmission level has been reduced from -3 dB for the open-loop LWA to -18 dB for the power-recycling LWA system. This indicates that the power at port 2, which is usually wasted in the load in the conventional open-loop LWA, has been nullified in the power-recycling system. This conventionally lost power is now recycled back into the input of the LWA to increase the overall system radiation efficiency. The transient role of the matched load at the Δ port will be explicated in the time-domain analysis of Section IV.

Fig. 5(b) shows the radiation efficiency of the open-loop LWA and the power-recycling LWA. The open-loop (or isolated) LWA has an efficiency close to 50%, resulting typically from a tradeoff between directivity or gain and size. Within the power-recycling system, the efficiency of the LWA has been enhanced to a value of 95%, very close to the ideal case of 100%. Further matching optimization would certainly increase this performance. In this simulation, ohmic and dielectric losses have been set to zero in order to validate the fundamental theory of this section, and the difference from 95% to 100% is therefore due exclusively to minor mismatches across the system. These results provide an idea of the maximum possible efficiency enhancement, using high-quality substrates. The actual enhancement attainable in practical implementation with a commercial substrate will be demonstrated experimentally in Section V.

TABLE I
HARMONIC BALANCE (AGILENT ADS) SENSITIVITY ANALYSIS FOR A 3-dB POWER-RECYCLING LWA (FIG. 3) USING AN IDEAL RAT-RACE, IDEAL TRANSMISSION LINES OF LENGTH θ, AND MODELING THE LWA BY AN ATTENUATOR. $\Delta\theta$ IS THE DEVIATION FROM THE DESIRED FEEDBACK PHASE θ, GIVEN IN (7B). THE INPUT POWER IS $P_i = 0$ dBm AND THE POWER P_Σ IS GIVEN IN dBm

	2.7-dB LWA	3.0-dB LWA	3.3-dB LWA
$\Delta\theta = -15^o$	$P_\sum = 3.18$ $\eta_s = 96.3\%$	$P_\sum = 2.87$ $\eta_s = 97.0\%$	$P_\sum = 2.59$ $\eta_s = 96.6\%$
$\Delta\theta = 0^o$	$P_\sum = 3.33$ $\eta_s = 99.7\%$	$P_\sum = 3$ $\eta_s = 100\%$	$P_\sum = 2.73$ $\eta_s = 99.8\%$
$\Delta\theta = +15^o$	$P_\sum = 3.17$ $\eta_s = 96.1\%$	$P_\sum = 2.87$ $\eta_s = 97.0\%$	$P_\sum = 2.59$ $\eta_s = 96.6\%$

Finally, Table I quantifies the impact of deviations from the conditions of (7) in terms of sum-port power P_Σ and system efficiency, η_s for a 3-dB power-recycling system, with an input power of $P_i = 0$ dBm. The center of the table indicates the optimal case considered above where the LWA exhibits exactly 3-dB attenuation (which may also include all possible losses), yielding $\eta_s = 100\%$ and $P_\Sigma = 3$ dBm, which is twice the power at the input port, consistently with $P_\Sigma = G_s P_i$, where G_s is given by (9) and shown to be equal to 3 dB in Fig. 4(b) for $\eta_0 = 0.5$. Moving horizontally, the table from this point shows the effect of a deviation from a 3-dB attenuation in the LWA, which is a reduction of both P_Σ and η_s, as may have been expected since conditions (7) are not exactly satisfied any more. Ohmic, dielectric, and mismatch losses would naturally tend to increase the attenuation, toward the right-hand side of the table. Moving vertically in the table from the center row shows the effect of a deviation from a $3\pi/4 + \mathrm{m}\pi$ phase in feedback-loop transmission lines, which is again a reduction of both P_Σ and η_s. What is most important to note is that deviations do *not* ruin the performances of the power-recycling system but only degrade them progressively as they increase.

IV. BUILD-UP OF THE WAVE FROM THE TRANSIENT TO THE STEADY-STATE REGIMES

The transient operation of the power-recycling LWA system may not be obvious from the previous descriptions. For instance, how can the power build up to produce of power at the sum port which becomes twice that of the input port? It is the purpose of the present section to clarify and illustrate the transition of the system from the transient to the steady-state regimes. It will be seen that power is irreversibly dissipated in the load

TABLE II
TRANSIENT BEHAVIOR OF THE IDEAL (NO LOSS, NO DELAYS) 3-dB POWER-RECYCLING LWA SYSTEM OF FIG. 3, COMPUTED BY (12). PASSES REFER TO PASSES OF THE WAVE ACROSS THE LWA FROM THE ONSET OF THE SYSTEM. THE POWER LEVELS ARE IN dBm AND $P_i = 0$ dBm

Time	P_i	P_Σ	P_f	P_Δ
Pass 0	0	−3.01	—	−3.01
Pass 1	0	0.51	−6.02	−9.03
Pass 2	0	1.85	−2.50	−15.05
Pass 3	0	2.45	−1.16	−21.07
Pass 4	0	2.73	−0.56	−27.09
Pass 5	0	2.87	−0.28	−33.11
Pass 6	0	2.94	−0.14	−39.13
Pass 7	0	2.98	−0.07	−45.15
Pass 8	0	2.99	−0.03	−51.18
Pass 9	0	3.00	−0.02	−57.20

of the Δ port in the transient regime. However, the proposed system is intended to operate in the steady-state regime, where the switch-on transient regime is safely considered a negligible ratio of the operation duration of the antenna system. The efficiencies of Section III naturally refer to the steady-state regime. Without loss of generality, this section considers the particular case of a 3-dB power-recycling LWA system.

A. Mathematical Calculation of Powers

To first gain a quick and basic intuitive perception of the transient response, let us consider a simplified mathematical model of the system, neglecting frequency and exact propagation delay consideration. In reference to Fig. 3, we excite the system by a $P_i = 0$ dBm $= 1$ mW signal, which corresponds to the initialization $V_i = \sqrt{2Z_0P_i} = 0.316$ V and $V_f = 0$ V. From this point, the voltages V_Σ, V_Δ, and V_f may be computed versus the number of passes of the signal across the feedback loop using the following algorithm:

$$V_\Sigma = \frac{V_i + V_f}{\sqrt{2}}$$
$$V_\Delta = \frac{V_i - V_f}{\sqrt{2}}$$
$$V_f = \frac{V_\Sigma}{\sqrt{2}}. \tag{12}$$

The resulting powers are listed in Table II. Initially, before the signal had time to penetrate into the feedback loop (so that the loop is invisible to the rat-race), the input power equally splits between the Σ and Δ ports. After the first pass, the signal appears at the f port, thereby more than doubling P_Σ slightly beyond P_i. At this time, a significant amount of power (around -9 dB $= 0.125$ mW) is still present at the Δ port, since P_i and P_f are still very different. As the number of passes increases, we have $P_f \to P_i, P_\Sigma \to 2P_i$ (as predicted in the steady-state analysis of Section III) and $P_\Delta \to 0$ mW. This shows that the Δ port acts as a power regulator. Initially, its load Z_L absorbs the excess power $P_i - P_f$, until P_f has reached the level of P_i, which corresponds to the steady-state regime, where it serves only for matching.

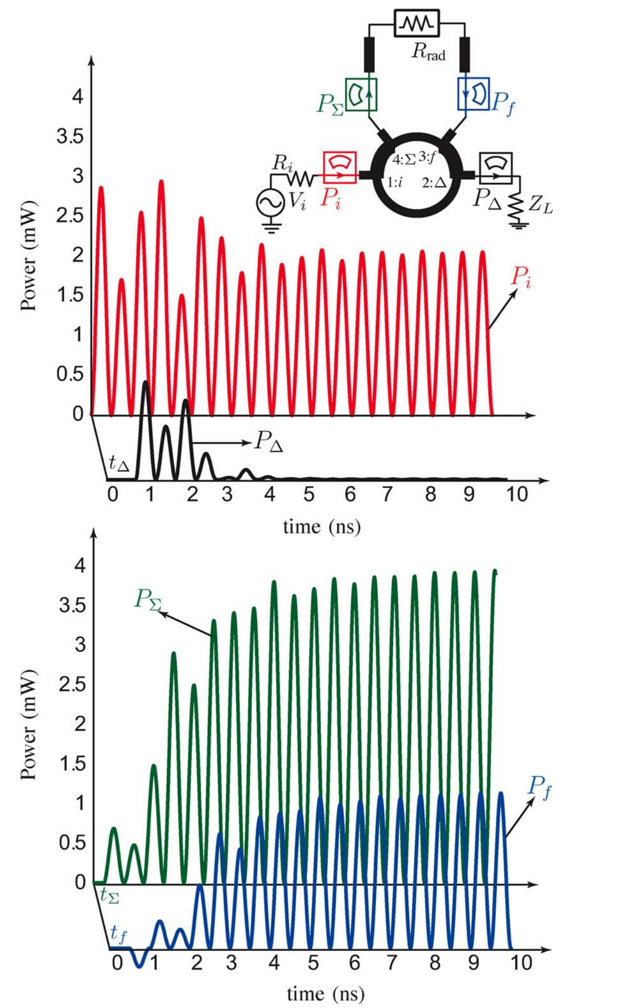


Fig. 6. Transient response (Agilent ADS) of the 3-dB power-recycling LWA system of Fig. 3, using an ideal rat-race coupler, ideal feeding transmission lines of length $\ell_{45} = \ell_{63} = 3\pi/4$, and a 3-dB resistive attenuator. The system is excited by a 1-GHz harmonic source of peak voltage $V_i = 0.316$ V (0 dBm in a 50-Ω system).

B. Circuit Simulation of Instantaneous Power Waveforms

The algorithm of the previous section was an oversimplified model of the actual power-recycling system. Let us now perform rigorous circuit simulation, exactly taking into account frequency and propagation delays across the rat-race and the feedback loop. In this simulation, the only simplifications will be the modeling of the LWA by an attenuator, the utilization of an ideal model for the rat-race, and the absence of loss. The excitation frequency is arbitrarily chosen as 1 GHz, corresponding to harmonic period of $T = 1/f = 1$ ns, and the source power was set to 1 mW.

Fig. 6 shows the transient evolution of the *instantaneous powers* at ports i, Σ, f, and Δ. The source is switched on at $t = 0$. Therefore, at this time, the corresponding power P_i is immediately present, whereas it did not have time to reach the other ports. Next, the wave splits into two waves toward the left and right of the input port along the rat-race. The times for the waves to reach the Σ, f, and Δ ports are $t_\Sigma = T/4 = 0.25$ ns, $t_f = T/2 = 0.5$ ns, and $t_\Delta = 3T/4 = 0.75$ ns, respectively. After these times, the exact transient behavior of

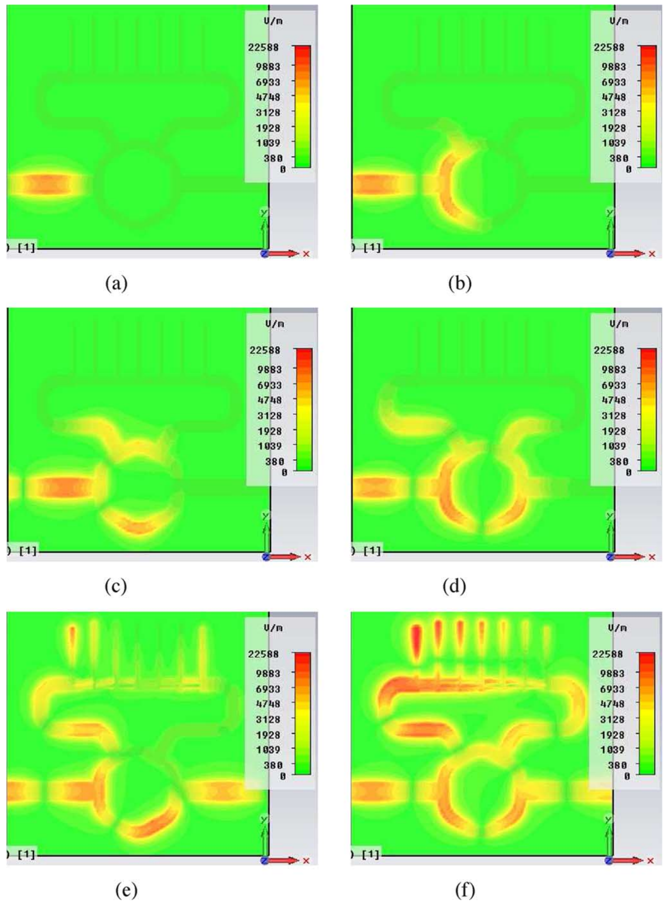


Fig. 7. Full-wave simulated (FIT, CST Microwave Studio) transient electric-field distributions for the power-recycling 3-dB LWA system of Fig. 3 with parameters of Fig. 5 at different instants. The excitation frequency is $f = 4.58$ GHz, corresponding to the harmonic period of $T = 1/f = 0.218$ ns. (a) $t_0 = 0.137$ ns, (b) $t_1 = t_0 + T/4 = 0.192$ ns, (c) $t_2 = t_0 + T/2 = 0.246$ ns, (d) $t_3 = t_0 + 3T/4 = 0.301$ ns, (e) $t_4 = t_0 + T = 0.519$ ns, and (f) $t_5 = t_0 + 8T = 1.884$ ns.

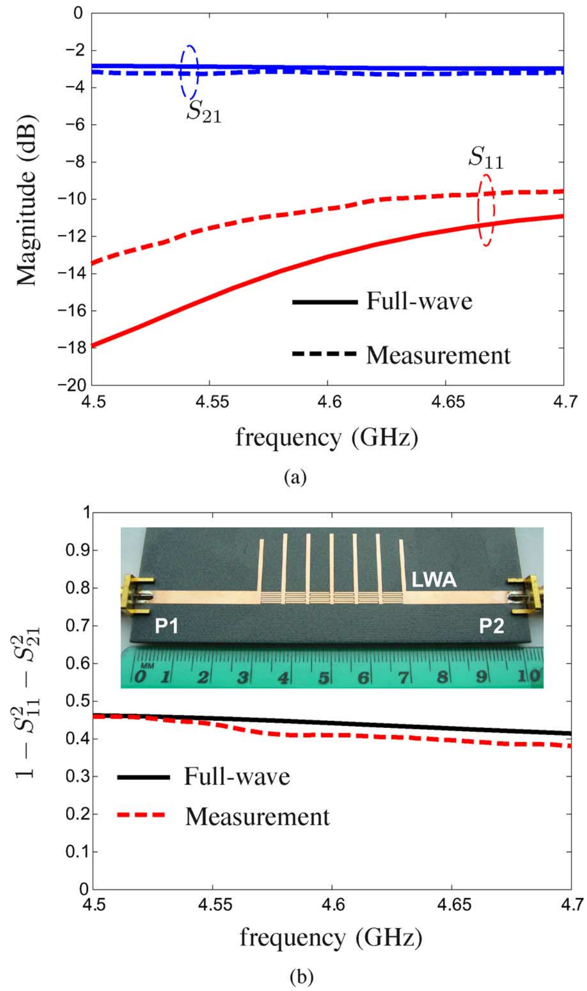


Fig. 8. Full-wave simulated (method of moments, Ansoft Designer) and measured scattering parameters for the 3-dB CRLH LWA prototype shown in the inset, which has the parameters given in Fig. 5, except for the number of unit cells which is here $N = 7$. (a) Return and insertion losses. (b) Dissipated power ratio, including radiation and loss power.

the signal, which lasts here for around 5 ns, can be observed on the curves, in agreement with the prediction of Table II. Initially, P_i is slightly varying and stabilizes to its nominal value of 1 mW only after the steady-state regime has been reached. This is because, at early times, the wave entering into the system does not see the other ports. Matching, as defined by scattering parameters, is valid only in the steady-state regime. P_Σ increases progressively to finally reach $2P_i = 2$ mW. P_f starts with a negative cycle. This is due to the fact that, during this time, $t_f < t < T$, the wave traveling in the lower arm of the rat-race toward the f port has not reached this port yet so as to cancel out with the wave traveling in the upper arm; in fact, the lower arm wave is reaching the f port only at time T. From that time, P_f grows to stabilize at the same level of the input power, $P_i = 1$ mW, in the steady-state regime. Finally, P_Δ quickly decays from t_Δ to fully vanish, as expected from satisfaction of the system's conditions (7).

C. Full-Wave Simulation of Electromagnetic Fields

The transient electromagnetic field distributions are plotted in Fig. 7 for the 3-dB power-recycling LWA system of Fig. 3 with parameters of Fig. 5. These results are self-explanatory. The evolution of the system from the transient to the steady-state regime can be followed step by step by using the same description the previous paragraph (ignoring the numerics). Optimal understanding of the system's operation may be gained by considering in parallel the results of Figs. 6 and 7.

V. Experimental Demonstration

Here, we present the experimental performance of the proposed power-recycling LWA system, again for the 3-dB case, by comparing the open-loop and feedback system responses. Real ohmic and dielectric losses are naturally present in this case, and therefore the results of this section provide a realistic assessment of the efficiency enhancement capability of the system.

A. Open-Loop (Isolated) LWA

Fig. 8(a) shows the scattering parameters for the isolated (open-loop) microstrip CRLH LWA shown in the inset of Fig. 8(b). This antenna was designed to dissipate a combined radiation and loss power, computed by $1 - S_{11}^2 - S_{21}^2$ and shown in Fig. 8(b), close to 3 dB for a 3-dB power-recycling

TABLE III
GAIN, DIRECTIVITY, AND EFFICIENCY FOR THE OPEN-LOOP LWA OF FIG. 8 AND FOR THE POWER-RECYCLING LWA OF FIG. 9

	Open-loop LWA ($\eta = \eta_0$)		Feedback LWA ($\eta = \eta_s$)	
	Full-wave	Measured	Full-wave	Measured
G	3.68 dB	3.70 dB	6.73 dB	5.77 dB
D	7.84 dB	7.88 dB	7.85 dB	7.42 dB
η	38.36%	38.00%	77.27%	68.45%

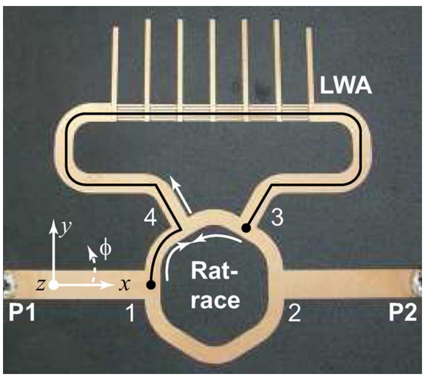


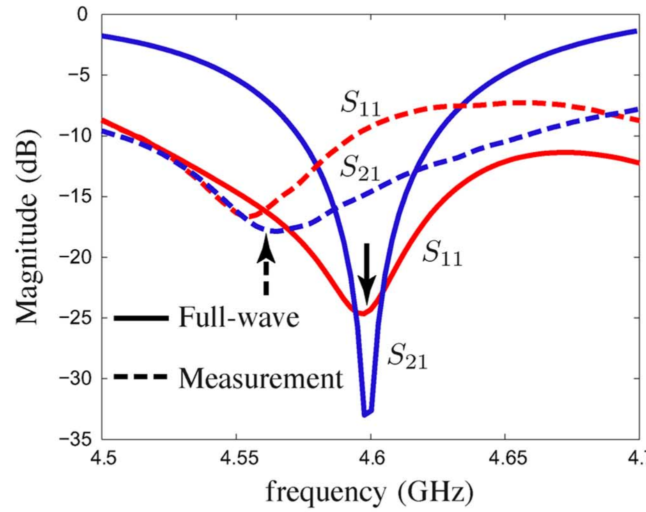
Fig. 9. Power-recycling 3-dB LWA prototype using the same antenna as in Fig. 10 with relevant phase shifts and power-flow indications. The total phase shift from port 1 to port 3 along the solid line is: $\ell_{14} + \ell_{45} + \ell_{\text{LWA}} + \ell_{63} = \pi/2 + 7\pi/4 + 0 + 7\pi/4 = 4\pi$ ($\ell_{\text{LWA}} = 0$ since the CRLH LWA is operated here at broadside).

system. The gain, directivity, and efficiency performances of this antenna are listed in the left-hand side of Table III. The measured radiation efficiency is of only $\eta_0 = 38\%$, which is a poor performance compared with the ideal value of $\eta_0 = 50\%$. A 12% degradation of the radiation efficiency is largely attributed to the mismatch (7.94% computed from measured S_{11} of -11 dB) and ohmic/dielectric losses of the open-loop microstrip CRLH LWA.

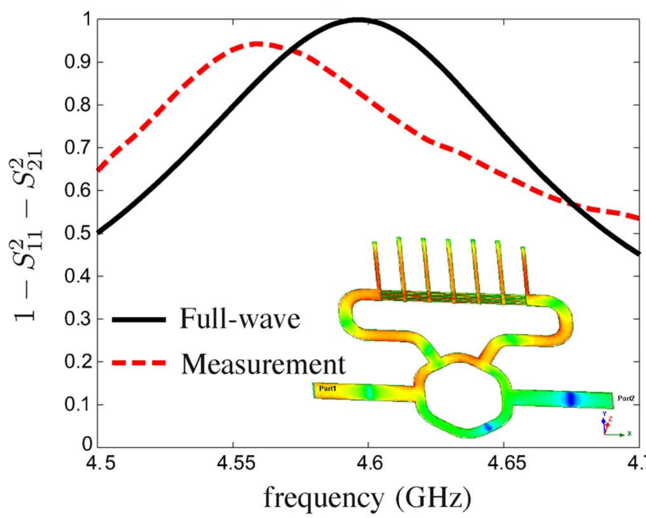
B. Power-Recycling LWA System

The antenna of Fig. 8 is now inserted into a 3-dB power-recycling system. This leads to the layout of Fig. 9, where the microstrip CRLH LWA and the rat-race coupler have been integrated on the same substrate. The resulting antenna system occupies an area that is more than twice the area of the original antenna. However, the size of the nonradiating part of the system (coupler and feeding lines) can be dramatically reduced by using a substrate with a higher permittivity, by exploiting the space at the back side of the antenna, or by implementing the rat-race coupler with lumped elements. Since the paper focuses on the *concept* of power-recycling rather than its specific implementation, no effort has been made along the direction of size reduction in the structure of Fig. 9. The scattering parameters and dissipated power for this structure are shown in Fig. 10. In the full-wave simulation, essentially all of the power has been dissipated ($S_{21} = S_{11} = 0$), while around 94% of the power has been dissipated in the experimental case.

The gain, directivity, and efficiency performances are given in the right-hand side of Table III. The full-wave and experimental radiation efficiencies are of 77.27% and 68.45%, respectively. This represents enhancements by factors of 2.01 and



(a)



(b)

Fig. 10. Full-wave simulated (method of moments, Ansoft Designer) and measured scattering parameters for the power-recycling 3-dB LWA system shown in Fig. 9. (a) Return and insertion losses. (b) Dissipated power ratio, including radiation and loss power. The inset shows the steady-state regime simulated electric field distribution.

1.80, respectively, corresponding fairly well to the system gain of $G_s = 2$ expected from (9) and Fig. 4 for a 3-dB system.

The degradation of measured radiation efficiency of 68.45% from the ideal 100% power-recycling LWA system efficiency is attributed to mismatch and ohmic/dielectric losses present in the LWA and rat-race coupler constituting the feedback system. As noted in the previous section, the losses in the open-loop LWA correspond to a 12% degradation of the open-loop radiation efficiency η_0. In the 3-dB feedback system where the power-recycling gain $G_s = 2$, this degradation results in a 24% reduction of system radiation efficiency η_s according to (10). The imperfect design of the rat-race coupler (in measurement, $S_{11} \approx -15$ dB and $S_{21} \approx -18$ dB in Fig. 10(a), while they should ideally be $-\infty$, meaning that a small amount of power is still reflected to the source and dissipated in the load in the steady-state regime) reduces approximately an addition 6% of system radiation efficiency. The remaining 1.55% degradation

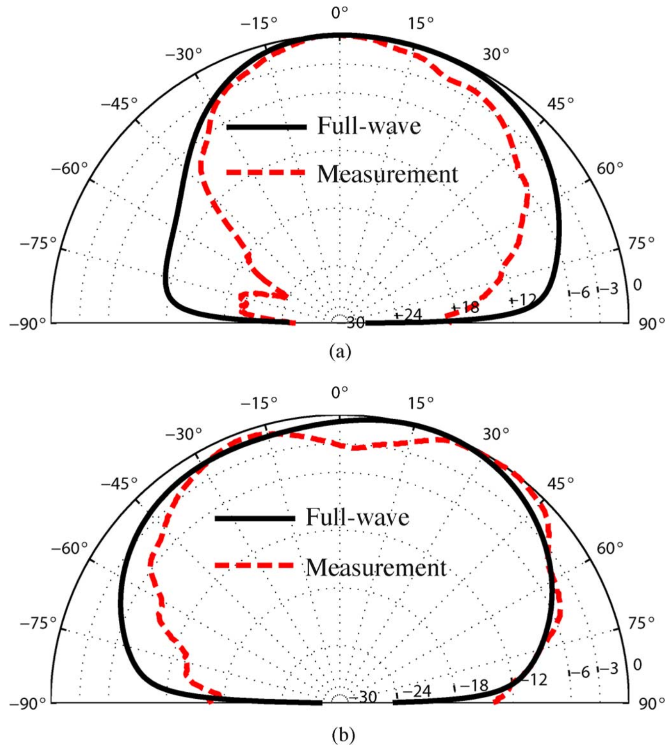


Fig. 11. Full-wave simulated (method of moments, Ansoft Designer) and measured radiation patterns for the power-recycling LWA of Fig. 9 (a)$\phi = 0°$ plane (E-plane). (b) $\phi = 90°$ plane (H-plane).

of radiation efficiency can be attributed to the ohmic/dielectric losses of the rat-race coupler and feeding transmission lines.

Finally, the radiation patterns of the structure are plotted in Fig. 11. The asymmetry in the E-plane [Fig. 11(a)] may first appear surprising, since the system's topology is perfectly symmetric with respect to the yz-plane. The reason for this asymmetry is that the structure *electromagnetically asymmetric*, since the Δ port is cold, as clearly visible in the inset of Fig. 10(b).

VI. Conclusion

Conventional LWAs provide high directivity while featuring a simple architecture, but suffer from low radiation efficiency, which is often prohibitive in practical applications with size restriction, since all of the power that has not been radiated when reaching their end is dumped into the load. This paper has proposed a general solution to this fundamental problem: a novel power-recycling feedback system, which feeds back the nonradiated power to the input of the LWA through a power-combining system. This power-combining system is a rat-race coupler, which constructively adds the input and feedback powers while ensuring perfect matching and isolation of the two signals, thereby dramatically enhancing the antenna's efficiency. Specifically, the radiation efficiency of the isolated (or open-loop) LWA, η_0, is enhanced by the system's gain factor $G_s (G_s > 1)$ to the overall radiation efficiency of $\eta_s = G_s \eta_0$, which may reach 100% for any value of η_0 in a lossless system.

The design conditions of the power-recycling system, depending on η_0, has been derived for a rat-race-based implementation, in the form of rat-race impedance ratios and feedback phase conditions. The build-up of the steady-state regime from the transient regime at the onset of the system has been explicated by transient circuit and electromagnetic simulations, and an experimental power-recycling LWA system has been demonstrated, where the isolated antenna efficiency η_0 is enhanced from 38% to 68%, corresponding to a system efficiency enhancement of $G_s = 1.8$. The proposed power-recycling feedback scheme applies to all LWAs and solves their fundamental efficiency problem in practical applications involving a tradeoff between relatively high directivity (higher than half-wavelength resonant antennas) and small size (smaller than open-loop LWAs or complex phased arrays).

In this study, the power-recycling feedback system was designed for fixed CRLH LWA broadside radiation. The authors are currently extending this design for frequency [8] and electronic [9], [10] full-space scanning capabilities by incorporating phase shifting elements in both the feedback loop and the power combiner. This will lead to a LWA structure with both maximal efficiency and full-space scanning capabilities.

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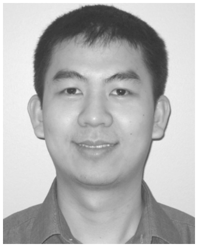

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