Compact Class-F RF-DC Converter with Antisymmetric Dual-Diode Configuration

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***Abstract*—A compact configuration of a 2.45-GHz microwave to dc power conversion circuit realizing a class-F operation is proposed. In the ideal class-F operation, harmonic power dissipations are eliminated by open and short terminations for the odd and the even harmonics, respectively. The proposed antisymmetric configuration of two single-shunt-diode rectifiers do not need explicit filters for the even harmonics. A design example that contains an impedance matching network at the fundamental frequency and a third-harmonic rejection filter is presented. Simulation results show that it also realizes approximately short terminations for the second and the fourth harmonics. A fabricated circuit achieved 77.9% RF-dc conversion efficiency when 27-dBm power of 2.45-GHz microwave was supplied.**

***Index Terms*—Class-F harmonic termination, RF-dc converter, wireless power transmission**

I. Introduction

Radio frequency to dc (RF-dc) converters are essential components in microwave power transmission systems. As demands of wireless charging technologies for mobile devices as well as for tiny wireless sensor nodes increase, smaller size and higher efficiency are desired.

RF-dc conversion systems including the source and the load typically consist of five elements: 1) the RF source, 2) an input filter, 3) one or several number of diodes, 4) an output filter, and 5) the load. To achieve higher efficiency, design of the filters are important.

In the frequency domain, the diodes generate harmonics, and the filters therefore have to reject power dissipation by those harmonics to improve the conversion efficiency. A fundamental requirement for the filters to reduce harmonics power dissipation is having a reflection coefficient nearly equal to 1 (ideally equal to 1 but actually less than 1) at every harmonic frequency. Additionally, the efficiency also depends on the arguments of the complex reflection coefficients, which affect the voltage and the current waveforms across the diodes and determine the maximum power handling capacity while not damaging or breaking down the diodes [1].

In the field of RF power amplifiers (PAs), the similar filter design is also considered, and PA operations can be classified into class-C, E, and F, with respect to the harmonic termination phase combinations [2]. For conventional Schottky barrier diodes with a low breakdown voltage and a relatively large on-state resistance, a set of harmonic terminations corresponding to the class-F operation is the most efficient [1].

In this paper we propose a compact configuration of RF-dc converter that realizes approximate class-F harmonic terminations. Conventional class-F rectifiers are composed of several numbers of microstrip stub filters [3]. The proposed configuration eliminates stub filters for even harmonics. We present a design example that has a third harmonic rejection filter and a fundamental impedance matching network. It was designed with the intention to be used in a two-dimensional waveguide power transmission system [4] and to be capable of handling at least 20-dBm RF input.

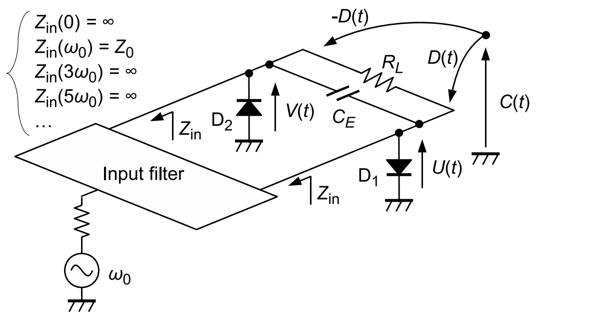

Fig. 1. A schematic diagram of the proposed circuit configuration. Two single-shunt-diode rectifiers are driven by a common-mode RF source. The input filter harmonic impedances $Z_{\rm in}(k\omega_0)$ ($k = 0, 1, 2, ...$) seen by each diode are high impedance at dc and odd harmonics. Only at the fundamental frequency, the impedance $Z_{\rm in}(\omega_0)$ presents a finite value Z_0, and it should be determined by considering conjugate impedance matching between the rectifier circuit and input filter.

Section II theoretically describes the proposed circuit operation. In Section III, approximate class-F harmonic terminations up to the fourth harmonic is demonstrated through simulations. Section IV presents that the measured conversion efficiency achieved 77.9% at a maximum. Finally this paper is concluded in Section V.

II. Antisymmetric Dual-Diode Configuration

This section describes the operation of antisymmetrically configured two single-shunt-diode rectifiers shown in Fig. 1. "Antisymmetric" refers to the rectifier circuit patterns symmetric to each other except for the opposite diode polarities. The rectifiers are driven by the common-mode RF input and convert it into the differential-mode dc power. In this configuration, the even harmonics generated by each diode are short-terminated, as described below.

Suppose that the two diodes have the same characteristics. Let $U(t)$ and $V(t)$ represent the voltage waveforms across diodes D_1 and D_2, respectively. The on-off sequences of the

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diodes are out of phase by a half cycle due to the opposite polarities. Besides, the voltage waveforms are inverted with respect to the ground. Therefore

$$U(t) = -V(t + T_0/2), \tag{1}$$

where T_0 represents the period of the waveform.

$U(t)$ and $V(t)$ can be expanded into the Fourier series:

$$U(t) = U_0 + \sum_{k=1}^{\infty} U_k \cos(k\omega_0 t + \theta_k) \tag{2}$$

$$V(t) = V_0 + \sum_{k=1}^{\infty} V_k \cos(k\omega_0 t + \theta_k), \tag{3}$$

where $\omega_0 \equiv 2\pi/T_0$ denotes the fundamental angular frequency. Note that the constant values θ_k in the phases are common in both $U(t)$ and $V(t)$. Substituting (2) and (3) into (1), we derive

$$U_0 + \sum_{k=1}^{\infty} U_k \cos(k\omega_0 t + \theta_k) = -V_0 - \sum_{k=1}^{\infty} V_k \cos(k\omega_0 t + \theta_k + k\pi), \tag{4}$$

therefore

$$U_k = \begin{cases} -V_k & (k = 0, 2, 4, ...) \\ V_k & (k = 1, 3, 5, ...). \end{cases} \tag{5}$$

Here we define the common-mode voltage $C(t)$ and the differential-mode voltage $D(t)$ as follows:

$$C(t) \equiv \frac{U(t) + V(t)}{2}, \qquad D(t) \equiv \frac{U(t) - V(t)}{2}. \tag{6}$$

From the above equations, we derive:

$$C(t) = \sum_{k=1}^{\infty} U_{2k-1} \cos\{(2k-1)\omega_0 t + \theta_{2k-1}\} \tag{7}$$

$$D(t) = U_0 + \sum_{k=1}^{\infty} U_{2k} \cos\{2k\omega_0 t + \theta_{2k}\}. \tag{8}$$

Thus, $C(t)$ contains only the fundamental and the odd harmonic components, and $D(t)$ contains only the dc and the even harmonic components.

In the proposed circuit, the differential-mode components are loaded with a resistor and an RF short capacitor. The RF short capacitor forces the RF components of $D(t)$, i.e. the even harmonic voltages, to be approximately zero while the dc component remains:

$$U_k \approx 0 \quad (k = 2, 4, 6, ...). \tag{9}$$

In addition, to realize perfect class-F harmonic terminations, the common-mode components have to be loaded with high-impedances at the odd harmonic frequencies except the fundamental frequency. Practically, a finite number of harmonics are considered and filters rejecting them are implemented. In the next section, we show the simplest case where only the third harmonic filter is implemented.

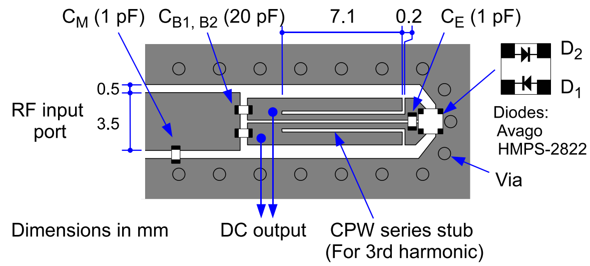

Fig. 2. Design example of the proposed circuit. The pattern is formed on one side of a 1.524-mm thick double-sided copper clad board, Arlon DiClad-880. Input microwave is fed from the 50-Ω coplanar waveguide (CPW) on the left hand side and conducted to the next 60-Ω CPW through the dc block capacitors C_{B1} and C_{B2}. The 60-Ω CPW live conductor is split at the center by a 0.2-mm thick slot for dc isolation. Inside the 60-Ω CPW, another smaller 60-Ω CPW is formed by L-shaped 0.2-mm thick slots. The smaller CPW is shorted at the left hand side end and is quarter-wavelength at the third harmonic frequency, the right hand side end become therefore open-circuited. Capacitor C_M is a part of an impedance matching network.

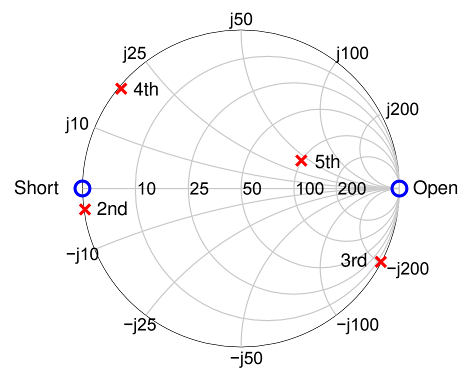

Fig. 3. Harmonic terminations of each diode. The terminations at the second and the fourth harmonics are approximately short, and one at the third harmonic is approximately open. The reflection coefficient at the fifth harmonic frequency is relatively low, because no filter is designed for this frequency.

In Takhedmit's work [5], two single-series configured diodes are driven by common-mode input and extract differential-mode dc power. The operation of that circuit can be also described similarly to the above, by interchanging the voltage and the current waveforms of the diodes. It corresponds to an inverse class-F operation, i.e. short terminations for the odd harmonics and open for even harmonics.

III. Design Example

This section presents a design example where only the third harmonic filter is implemented as shown in Fig. 2.

The circuit impedances seen by each diode at the harmonic frequencies up to the fifth harmonic were simulated by CST Studio Suite. In the simulation, diodes D_1 and D_2 were replaced with two RF signal sources and the reflection coefficients at the sources were calculated. The source signals are anti-phase for the second and the fourth harmonics, and are in-phase for the third and the fifth harmonics. The result shown in Fig. 3 demonstrates that the approximate class-F harmonic terminations up to the fourth harmonic is achieved.

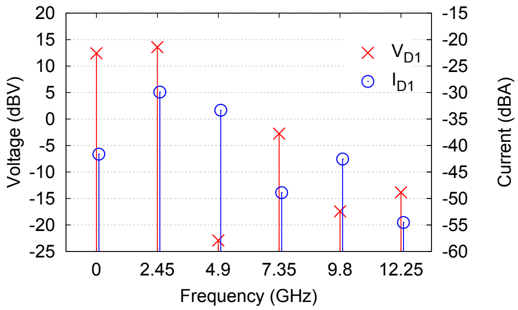

Fig. 4. Spectra of the simulated voltage and current across the diode D_1. The reference values are 0 dBV = 1 V and 0 dBA = 1 A.

The voltage and current spectra calculated through a harmonic balance simulation is shown in Fig. 4. The second and the fourth harmonic voltages and the third harmonic current are reduced.

IV. Measurement Result

The circuit described in the preceding section was fabricated as shown in Fig. 5. The evaluation setup is shown in Fig. 6. The incident RF power P_{in} is measured by the power meter, Agilent E4418B, through the directional coupler. The fundamental frequency component of the reflected power, P_{ref}, is measured by the spectrum analyzer, Agilent N9342C. The output voltage V_{out} across the load resistor R_L is measured by the voltmeter, and the power consumption at the load, P_{out}, is calculated as $P_{\mathrm{out}} = V_{\mathrm{out}}^2/R_L$. The frequency dependence and the input power dependence of the RF-dc conversion efficiency $P_{\mathrm{out}}/P_{\mathrm{in}}$ and the reflection coefficient $P_{\mathrm{ref}}/P_{\mathrm{in}}$ are shown in Fig. 7 and Fig. 8, respectively.

V. Conclusion

A compact class-F RF-dc converter was proposed. The fabricated circuit efficiency was 77.9% at a maximum, while the harmonic rejection filter was explicitly designed for only the third harmonic. As a future work, combinations with other filters that reject higher harmonics can improve the efficiency.

Acknowledgment

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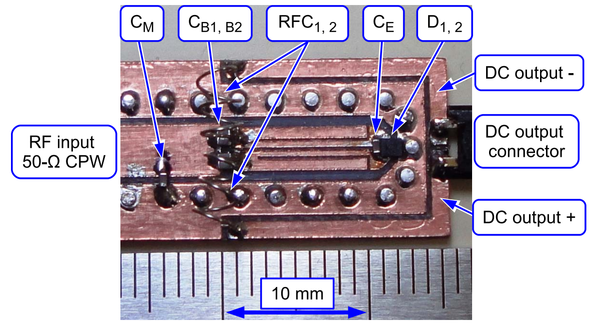

Fig. 5. A fabricated example. The dimensions are smaller than 20 × 10 mm^2. $RFC_{1,2}$ are 3-mm diameter, 3-turned coils made of a 0.26-mm thick tinned wire, and are used for the RF isolation and the dc connection.

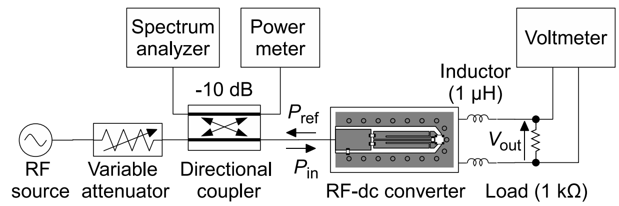

Fig. 6. Schematic illustration of the measurement setup. The frequency and the power of the microwave fed into the circuit are swept and the corresponding dc output are measured.

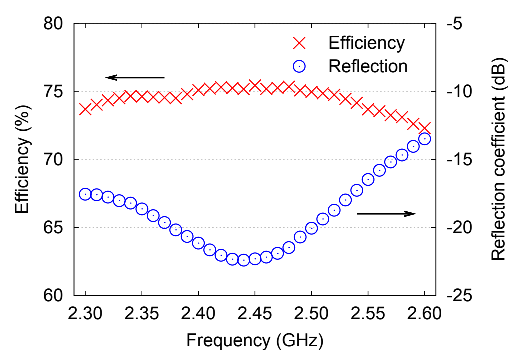

Fig. 7. Measured conversion efficiency and reflection coefficient versus frequency. The input RF power was fixed at 20 dBm. The peak efficiency is 75.4% at 2.45 GHz.

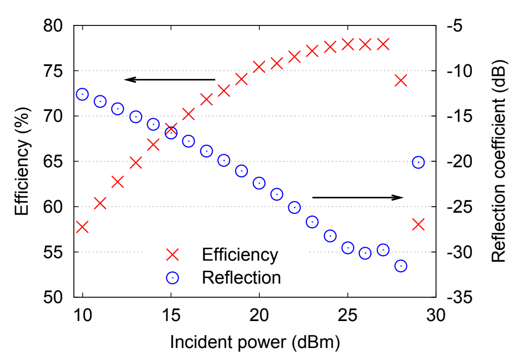

Fig. 8. Measured conversion efficiency and reflection coefficient versus input power. The RF frequency was fixed at 2.45 GHz. The peak efficiency is 77.9% at 27 dBm. Above 28 dBm, the output voltage (not shown here) saturates and the efficiency drops steeply, due to the breakdown voltage of the diodes.