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シングルダイオードを用いた周波数ダブラとマイクロ波-直流変換

～2 つの機能を有する無線電力変換器の測定システムの構築～

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あらまし　本報告では，ショットキーダイオードを用いた二次高調波での無線伝送実験を検討している．0 dBm の出力で周波数が 1.975GHz のマイクロ波を，直流電圧 (0.65 V) に変換することができる簡単な構成なシステムにおいて，マイクロ波-直流変換のプロセスで発生する第二次高調波は，1.975 GHz の 2 倍の周波数であり，再放射される．受電用のアンテナと再放射用のアンテナを分離することで，極近傍ではあるが二次高調波を受信できることを示し，そのピーク電力が-39.6 dBm であることを実験的に確認した．

キーワード　周波数ダブラ，高調波，マイクロ波-直流変換，整流器

Single Diode Frequency Doubler and Microwave-to-DC Conversion

～A Dual Functionality Wireless Power Transducer Measurement System～

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Abstract　The Schottky diode plays a large role in wireless power transfer and microwave-to-DC conversion. This report describes a simple circuit and measurement system that is capable to convert a 1.975 GHz, 0 dBm microwave single tone excitation to 0.65 V DC. In the microwave-to-DC conversion process, the generated 2nd harmonic is the doubler frequency and is re-radiated. Using a spectrum analyzer, the doubler frequency is measured at 3.95 GHz with peak amplitude of -39.6 dBm.

Key words　Frequency doubler, harmonics, microwave-to-DC, rectifier

1. Introduction

Most frequency multipliers are designed for the millimeter wave range applications [1] - [2]. In [1] it is shown that an array of frequency doublers is possible and simulations confirm an intuitive result that doubling efficiency is higher at lower frequency and increases with increase in input power but, there is an optimum point. In [2] it has been presented that an efficient frequency multiplier is achievable if all designs and power levels are optimized everywhere in the chain, and agrees with [1] that performance decreases with increasing operation frequency. However, [1] cites diode reverse breakdown voltage as a drawback, and [2] cites resistive losses.

While we acknowledge that various diode manufacturers have greatly improved their diode performances over the years, it is recommended that frequency doubler circuits use Schottky diodes [3] because they reliably exhibit low flicker noise and fast switching speeds in addition to a low barrier potential. A Schottky diode is therefore iconic both for rectenna based microwave-to-DC conversion and in this case, frequency doublers. This creates a paradox; a conflict of interest expounded by the following two points.

（1） In Schottky based microwave-to-DC conversion, there is need for harmonic suppression to increase the conversion efficiency.

（2） In Schottky frequency doublers, there is need to suppress only the higher-order odd harmonics (especially 3rd and 5th).

The above conflict of interest implies that, one has to design their circuit for either frequency doubler applications or for microwave-to-DC conversion but not both. This has been the trend until recently, for example a discussion in [4] examines selected few of the many frequency doublers and concludes that to reject the higher order odd harmonics, a balanced full wave diode bridge rectifier is necessary. As an improvement over the other frequency doubler circuits, which completely neglect the output DC component i.e. the rectified DC output, the work in [4] provides a simple path for the DC output but does not use the DC voltage at all. We think an opportunity is missed here.

In this work, we exploit a single Schottky diode circuit for both frequency doubling and microwave-to-DC conversion; a dual functionality. We optimize the circuit for high DC output, while a significantly higher amplitude level of double frequency is generated from the second harmonic and is monitored in real-time on a spectrum analyzer. At all cost, the proposed circuit is roughly optimized so that the 3rd harmonic though not eliminated, is as low as possible.

The proposed scheme is shown in Fig. 1 and is appropriate for measurements in the microwave frequency range. It is acceptable to design frequency doublers at such lower frequencies as long as upscaling design guidelines [4] without loss of generality are possible to provide upon request or when need be.

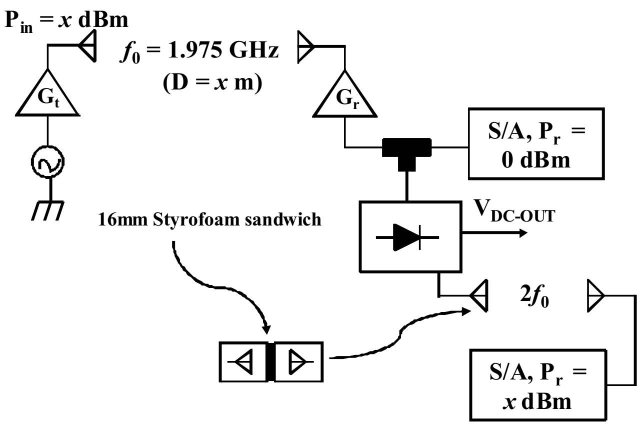


Fig. 1 Frequency doubler and Microwave-to-DC conversion configuration. S/A is the spectrum analyzer for real-time peak monitoring.

The organization of this paper is as follows. Section II presents the proposed single diode rectifier circuit configuration. In Section III, the configuration and measurement circuit for $2f_0$ generation is presented. Section IV presents the design, fabrication and performance of f_0 antenna while Section V presents the design, fabrication and performance of $2f_0$ antenna. The measured results for the double frequency ($2f_0$) and the instantaneous DC voltage conversion are presented in Section VI. Finally, Section VII concludes this paper.

2. Single diode rectifier configuration

This paper proposes a simple rectifier built around a single HSMS-282 Schottky diode.

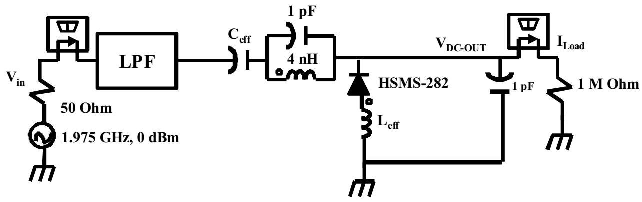


Fig. 2 The proposed single diode rectifier circuit configuration.

In the circuit of Fig. 2, matching was achieved by tuning the L-C branch at the input. Optimized values are L = 4 nH and C = 1 pF. Higher order odd harmonic suppression and improvement of DC conversion was achieved by tuning the grounding effective inductance, L_{eff}. Generally,

$$1.5nH \leqq L_{eff} \leqq 22nH \quad (1)$$

.

For circuit tuned frequency synchronization with the single tone excitation, C_{eff} is used. Generally,

$$1pF \leqq C_{eff} \leqq 10pF \quad (2)$$

.

2.1 Design in ADS

During simulations in Agilent's ADS, a 0.5 dB ripple Chebyshev LPF was used to block entry of higher order harmonics towards the tone generator. During fabrication, an antenna that by design cuts out all higher order harmonics is ideal for use.

Theoretically, the circuit of Fig. 2 outputs a DC component plus harmonic amplitudes, given a single tone excitation. The output can be modeled by Taylor series expansion. Harmonic balance tuning methods in ADS plots the output of Fig. 2 as in Fig. 3.

In Fig. 3, a high DC voltage conversion is achieved, unfortunately associated with a fundamentally high amplitude first harmonic f_0. The $2f_0$ amplitude equals -40 dBm and is significantly measurable. A spectrum analyzer with a noise floor around -60 dBm is earmarked for these measurements.

2.2 Rectifier fabrication on PCB

FR4 dielectric substrate was used. The matching was implemented by a simple quasi T structure [5]. Given a 1.975 GHz, 0 dBm single tone excitation, the instantaneous measured DC voltage was 0.65 V.

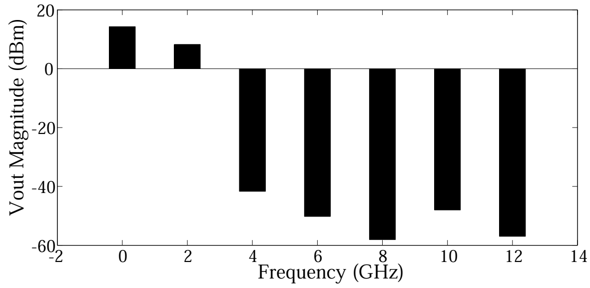


Fig. 3 The single diode output, approximated by Taylor series.

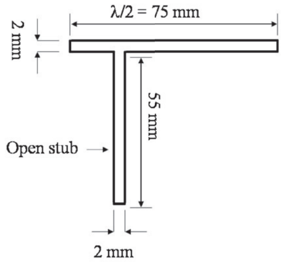


Fig. 4 Quasi T structure matching strip.

The geometry of the matching strip in Fig. 4 can be changed to a form that is size optimal if miniaturization becomes an issue.

3. Configuration and measurement circuit for $2f_0$ generation

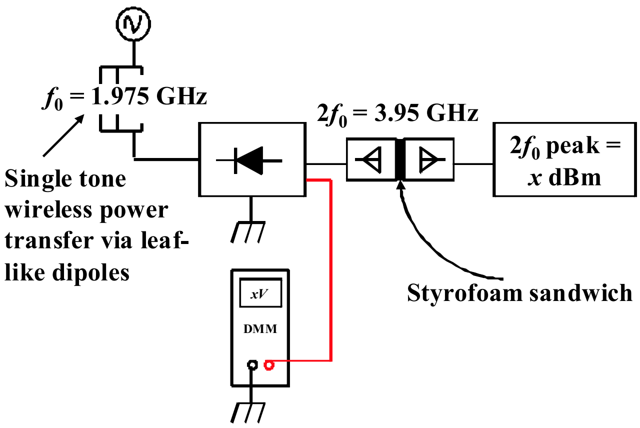


Fig. 5 Configuration and measurement circuit for $2f_0$ generation

The measurement configuration presented in Fig. 5 presents the need to design two leaf-like dipole antennas for circuit excitation and two patch antennas for the Styrofoam sandwich double frequency power transmission. The 16 mm Styrofoam is used to fix the two $2f_0$ patches at close distance and hence reducing the propagation loss of the $2f_0$ signal. The measured loss across or through the 16 mm sandwich equals 9.9 dB.

4. Design for f_0 antenna

4.1 Design geometry and performance characteristics

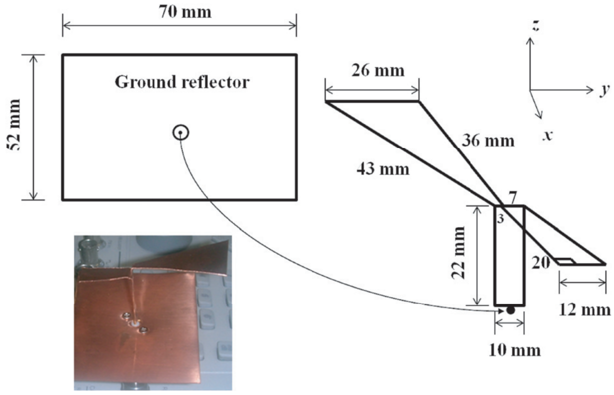
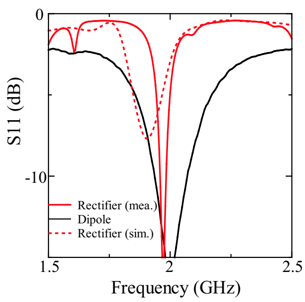
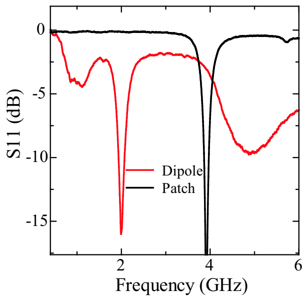


Fig. 6 Leaf-like dipole antenna geometry

The leaf-like dipole geometry in Fig. 6 is simple to construct, low cost and exhibits wide band performance characteristics as shown in Fig. 7 (a) compared to the narrow band of the low profile patches at $2f_0$, Fig. 7 (b). The design and radiation performance of these patches are described in the later section.



(a) Dipole vs. rectifier.



(b) Dipole vs. patch.

Fig. 7 Leaf-like dipole exhibit wide band characteristic desirable at the fundamental frequency to contain the tuned performance of the rectifier.

The dipoles have wide band S_{11} characteristic compared to the narrow band characteristic of the rectifier input. It is by design that the rectifier operates within the antenna's -10 dB S_{11} bandwidth (FBW). However, the dipole does not have the desired characteristics at the multiples of the fundamental frequency; i.e. it is desired that the dipole perfectly cuts out higher multiple frequencies, in a fashion of the so called filtering antenna. This can be improved in future works.

5. Design for $2f_0$ antenna

For this purpose, a simple construction, ultra low profile geometry and directional gain, ideal for sandwiching to focus the double frequency power transfer is desired. A patch becomes a candidate for in which case, the geometry of Fig. 8 is befitting, where 18 mm is approximately the quarter wavelength at 3.95 GHz.

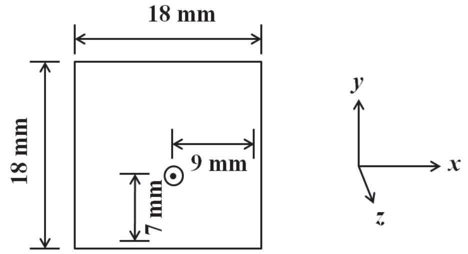
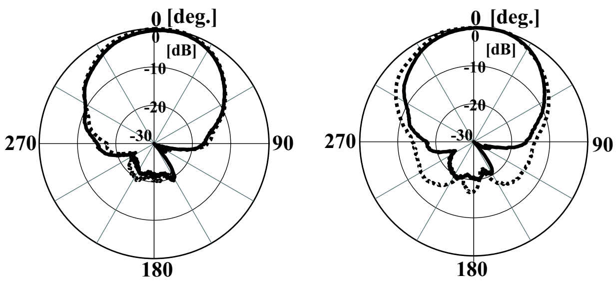


Fig. 8 Probe-fed patch antenna geometry

The performance characteristics of the patch radiation pattern are shown below. Further the influence of patch open sandwiched with a Styrofoam was examined, confirming that there is generally no loss in directive gain.



(a) Sandwich patch patterns. (b) Influence of Styrofoam.

Fig. 9 Design, fabrication and performance testing of Styrofoam sandwiched patches. The Styrofoam sandwich thickness is 16 mm; the patches are printed on FR4 substrate, $\epsilon_r = 4.8$, $t = 1.6$ mm, and $\delta = 0.01$.

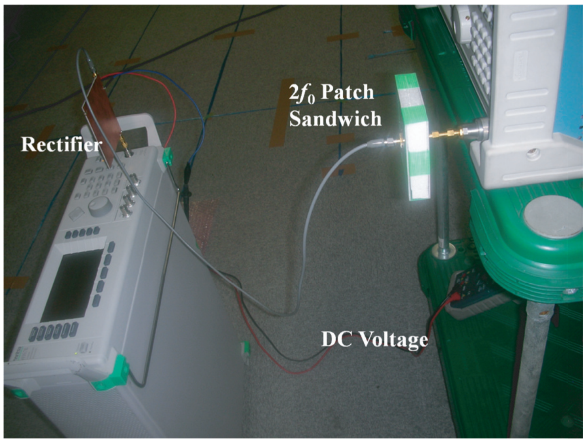
6. Measurement results

Using the measurement setup in Fig. 5, realized as in Fig. 10 (a), a double frequency amplitude equal to -39.6 dBm was measured as shown in Fig. 10 (b).

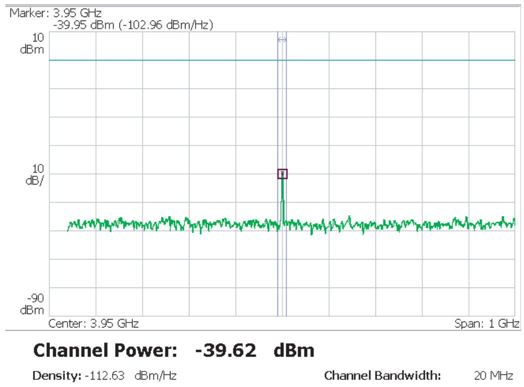
While observing the -39.6 dBm peak of the double frequency, we also monitored the DC voltage conversion. The measured DC voltage was equal to 0.65 V and depending on application e.g gate bias, switching, battery topping up etc, this could be useful.

7. Conclusion

In view of wireless power transfer and microwave-to-dc power conversion techniques, this work has proposed a very simple circuit to do both DC conversion and frequency doubling. Simulations in ADS have guided the measurement setup design and the doubled frequency results are comparable, -39.6 dBm (measurement) and -40 dBm (simulation).



(a) Setup



(b) $2f_0$ peak

Fig. 10 Physical realization of the measurement setup and the double frequency ($2f_0$) peak amplitude observation at 3.95 GHz. While the sandwiched patches are shown in the figure, the leaf-like dipoles are deliberately not shown in order to limit detail in the picture.

A reasonably high level of converted DC (0.65 V) was measured.

Future work will aim at providing excellent 3rd harmonic suppression while ensuring low conversion loss. Additionally, it is imperative to compute and measure the doubling efficiency and the dependence of 2nd harmonic power on the input power during single tone excitation.

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