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Two-Tone Excited Hybrid-Coupler-Based Intermodulation Generator for High-Isolation Wireless Sensing Applications

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ABSTRACT

An intermodulation generator is designed and presented with integration of a hybrid coupler and two identical Schottky diodes (i.e., D1 and D2). The connection polarities of D1 and D2 to the direct and coupled ports of hybrid coupler are opposite for its rapid realization of balanced intermodulation generation. Due to the superior coupling characteristics of hybrid coupler, it can distribute an incident two-tone signal to the direct and coupled ports evenly for D1 and D2, and deliver the balanced intermodulation generations to the isolation port highly insulated from its incident port. Two identical quarter-wavelength shorted stubs at the fundamental frequency are implemented by suppressing the second-order spectrums for an enhancement of the balanced intermodulation generations. Both theoretical analysis and experiments validate the presented intermodulation generator design, which can highly isolate its incidences (the two tones) and outputs (the intermodulation generations) for the future high-isolation wireless sensing applications.

INDEX TERMS

Hybrid coupler, two tones, intermodulation, schottky diodes, wireless sensing.

I. INTRODUCTION

With an increased number of sensor nodes in the internet of thing (IoT), wireless sensing has been an insurmountable task to capture atmospheric physics, e.g., humidity, temperature, and pressure. Most of the time, a wireless sensing system with properties of high reliability, low cost, compactness, and low-power consumption is preferred. Generally, a fully passive 2nd harmonic transponder can be an attractive candidate, and has been explored and developed since more than 50 years ago [1]. When a base station interrogates the harmonic transponder at the fundamental frequency (ω0), the 2nd harmonics (2ω0) are accordingly generated and backscattered, which can then be captured and demodulated by the base station for atmospheric physics data retrieves. On account of its high robustness to the environmental clutter interference, 2nd-harmonic transponders have been successfully employed into various scenarios, e.g., the foraging range of bumblebees research [2], wood frogs tracking [3], avalanche victim searching [4], and cracked wall monitoring [5], and etc.

To preserve a possibility of further 2nd harmonic recycling for a direct current (dc) current conversion enhancement (can be up to 25% of the fundamental incidences), an alternative 3rd harmonic generation from its high-efficiency rectification was recently exploited by implementing a hybrid coupler for the backscattering responses to align an antenna pair in a wireless power transfer (WPT) system [6], whose operation schematic is depicted in Fig.1. Because of the dual-mode characteristics of hybrid coupler, the fundamental interrogation (ω0) and the 3rd-harmonics (3ω0) response can be highly isolated. However, it heavily requires dual-band antenna pairs working at both the fundamental and 3rd harmonic frequencies to establish both the power and data wireless link between the base station and the terminal, which...
for the backscattering link establishment between the two horizontally-polarized (HP) antennas (i.e., TX2 and RX2). Both simulated and measured results validate that the two-tone excited intermodulation generator can produce and deliver the completed intermodulation to the isolation port highly isolated from the input port (P1), which brings a prospect for the future high-isolation wireless sensing by adopting a shared-aperture dual-polarized antenna.

II. THEORY ANALYSIS AND OPERATION MECHANISM

The two-tone excited intermodulation generator is provided in the dash box of Fig. 1. The connection polarities of D1 and D2 to the direct and coupled ports of the hybrid coupler are opposite for its rapid realization of balanced intermodulation generation [11], which enables a compact system realization without considering any matching networks. To enhance the balanced intermodulation generations, two identical quarter-wavelength shorted stubs at the fundamental frequency (ω0) followed by P2 and P3 of the hybrid coupler are implemented by suppressing the second-order spectrums. Since frequency offsets between the intermodulation and ω0 are insignificant (typically < 50 MHz), the hybrid coupler is thus capable of coupling and delivering both the two tones (ω1, ω2) and the intermodulation (ω1m1, ω1m2) generations within its effective frequency bandwidth simultaneously, whose S-parameters at the fundamental frequency (ω0) can be expressed as follows.

\[
S_{0ω0} = \begin{bmatrix}
0 & -i & -\frac{1}{\sqrt{2}} & 0 \\
-\frac{i}{\sqrt{2}} & 0 & 0 & -1 \\
-\frac{1}{\sqrt{2}} & 0 & 0 & -i \\
0 & -1 & \frac{i}{\sqrt{2}} & 0
\end{bmatrix}
\]  

(1)

To compare the intermodulation and the 3rd-harmonic generators in Fig. 1, the dual modes of hybrid coupler are analyzed. According to its odd-even mode analysis, S-parameters at the 3rd harmonic can thus be derived as given in (2). It should be noticed that the S-parameters at 3rd harmonic are similar to ones at the fundamental frequency except the phase differences of S21 (S12) and S33 (S34). Consequently, the hybrid coupler can operate at both the fundamental and 3rd harmonic frequencies.

\[
S_{3ω0} = \begin{bmatrix}
0 & +i & -\frac{1}{\sqrt{2}} & 0 \\
+i & 0 & 0 & -\frac{1}{\sqrt{2}} \\
-\frac{1}{\sqrt{2}} & 0 & 0 & +i \\
0 & -\frac{1}{\sqrt{2}} & +i & 0
\end{bmatrix}
\]  

(2)

To intuitively observe the properties of hybrid coupler, its S-parameters are simulated in the Advanced Design System (ADS), whose structure is realized with several ideal
microstrips. Since the structure of hybrid coupler is symmetrical, only magnitudes of $S_{11}$, $S_{21}$, $S_{31}$, and $S_{41}$, and phase differences of $(S_{11}-S_{41})$ and $(S_{21}-S_{31})$ of ADS simulation are given. The frequency is normalized from 0 to $4\omega_0$, which fully covers the fundamental and 3rd harmonic frequencies ranges, as illustrated in Fig. 2.

It is firstly assumed that the power levels of the single and the two-tone incidences are identical, which can be expressed as $V_S$ at the input port ($P_1$) of the hybrid coupler. Based on the S-parameters as provided in (1), $V_S$ can be then distributed to the direct (P2) and coupled (P3) ports while its isolation port (P4) maintains highly isolated. Therefore, the distributed signals at P2 and P3 can be calculated with

$$V_{\text{dir}} = -i\frac{V_S}{\sqrt{2}}$$

$$V_{\text{cou}} = -\frac{1}{\sqrt{2}}V_S$$

where $V_S = \sqrt{2}V_{IN}\cos\omega_0 t$ and $V_{S'} = V_{IN}(\cos\omega_1 t + \cos\omega_2 t)$ for the single-tone and the two-tone incidences, respectively. It can be observed that $V_{\text{dir}}$ and $V_{\text{cou}}$ have even magnitudes (except their phase differences), which is important for the balanced intermodulation generations from the two identical diodes of D1 and D2 [11]. Typically, the nonlinear output response (Vo) of D1 or D2 can be expressed by the Taylor series in terms of its incident signal [6], for example, Vo generated from D1 at P2 with an excitation of $V_{\text{dir}}$.

$$V_O = a_0 + a_1 V_{\text{dir}} + a_2 V_{\text{dir}}^2 + a_3 V_{\text{dir}}^3 + a_4 V_{\text{dir}}^4 + a_5 V_{\text{dir}}^5 + \ldots + a_n V_{\text{dir}}^n$$

where $a_0$, $a_1$, ..., and $a_n$ are the Taylor expansion coefficients. Only high-odd-order terms of $a_3 V_{\text{dir}}^3$ and $a_5 V_{\text{dir}}^5$ contribute to the 3rd harmonic and intermodulation, whose corresponding voltages generated by D1 and D2 at direct (P2) and coupled (P3) ports can thus be calculated with

$$V'_{\text{dir}} = i \left(\frac{a_3 V_{\text{IN}}^3 - 2a_5 V_{\text{IN}}^5}{4}\right) \times$$

$$+ i \left(\frac{12a_3 V_{\text{IN}}^3 - 25a_5 V_{\text{IN}}^5}{32\sqrt{2}}\right) \xi$$

$$+ i \left(\frac{12a_3 V_{\text{IN}}^3 + 25a_5 V_{\text{IN}}^5}{32\sqrt{2}}\right) \xi$$

where terms of $\chi = \cos 3\omega_0 t$ and $\xi = \cos \omega_{IM1} t + \cos \omega_{IM2} t$ for 3rd harmonic and intermodulation, respectively. To analyze the above the delivery of 3rd harmonic and intermodulation (6, 7) through the dual-mode hybrid coupler, the phase differences between $V'_{\text{dir}}$ and $V'_{\text{cou}}$, and corresponding power magnitudes should be initially evaluated. Since it is not possible to know the phase and power magnitude info directly from (6) and (7), the harmonic balance (HB) simulation from advanced design system (ADS) is performed to evaluate the coefficients of $a_3$ and $a_5$. The single-tone or the two-tone signal ($V_S$) is incident at the input ($P_1$) port of hybrid coupler. Then the mentioned phase differences and power magnitudes can be simulated respectively from Fig. 3. For the simple validation, the single tone incidence at frequency of $\omega_0 = 2\text{GHz}$ is selected without considering the authorized frequency band, such as the ISM, while the frequency space of the two tones diverse from the center frequency ($\omega_0 = 2\text{GHz}$) with $\Delta \omega = 0.02\text{GHz}$ (20 MHz), whose detailed parameters in the ADS and the implemented diodes information are provided in the Table 1.

| $\omega_1$ | $\omega_2$ | $\omega_0$ | $P_{IN}$ | $D_{D1}/D_{D2}$ |
|------------|------------|------------|---------|-----------------|
| 1.98 GHz   | 2.02 GHz   | 2 GHz      | $-10 + 10 \text{dBm}$ | HSMS2860 |
| 1.98 GHz   | 2.02 GHz   | 2 GHz      | $-10 + 10 \text{dBm}$ | SMS7630 |

Table 1. Detailed parameters setting in ADS simulation.

HSMS2860 is firstly selected to evaluated power magnitudes and phase differences at the direct (P2) and coupled (P3) ports of hybrid coupler respectively. As indicated by the phase and power magnitudes simulation from Fig. 3a and Fig. 3b, it can be noticed that 3rd harmonic generated from D1 and D2 at P2 and P3 respectively keeps equal, while its phase differences maintain approximately $-90^\circ$ ($-\iota$). Henceforth, only the term of $a_3 V_{\text{IN}}^3 \gg$ the term of $2a_5 V_{\text{IN}}^5$ in (6) and (7) can explain the equal power magnitudes and $-90^\circ$ ($-\iota$) phase differences of the 3rd harmonics at P2 and P3 of hybrid coupler. Similarly, the intermodulation generations from D1 and D2 can also be evaluated with an identical incident power, which is given in Fig. 3b. It indicates that within the power ranges of interest, the power magnitudes of $P'_{\text{cou}}$ and $P'_{\text{dir}}$ are closely equal. The differences in between are less than 2 dB even at an ultralow incident power level of $-10 \text{dBm}$. In the meantime, the power magnitude differences are continuously decreased ($-10 \sim +10 \text{dBm}$). Furthermore, with an increase
of the incident power, the phase differences between the in-ermodulation of $V_{\text{cou}}^*$ and $V_{\text{dir}}^*$ decrease incessantly, whose trend approaches $90^\circ$ ($+i$). With comparison of (6) and (7), only a condition under the term of $12a_3V_{\text{IN}}^3 < \text{term of } 25a_3V_{\text{IN}}^5$ can explain such ADS simulation results in Fig. 3b. Therefore, the coefficient of $a_3$ contributes to almost all the intermodulation generation when the interrogating power ranger is over $-10$ to $+10$ dBm.

Hence, the 3rd harmonic and intermodulation at the direct and coupled ports ($V_{\text{dir}}^*$ and $V_{\text{cou}}^*$ in (6) and (7)) of hybrid coupler can then be approximated to ones in (8) and (9). According to S-parameters provided in (1) and (2), $V_{\text{dir}}^*$ and $V_{\text{cou}}^*$ (both 3rd harmonic and intermodulation) can be totally delivered through the hybrid coupler to the isolation port ($P_4$) with high isolation from the input port ($P_1$) as demonstrated by (10), (11) as follows.

$$V_{\text{dir}}^* = -iV_{\text{cou}}^* = i\frac{a_3V_{\text{IN}}^3}{4}\cos3\omega_gt \quad (8)$$

$$V_{\text{cou}}^* = iV_{\text{cou}}^* = -i\frac{25a_3V_{\text{IN}}^5}{32\sqrt{2}}(\cos\omega_{\text{IM1}}t + \cos\omega_{\text{IM2}}t) \quad (9)$$

It is demonstrated that the 3rd harmonic and intermodulation generations at the direct and coupled ports of hybrid coupler have same magnitudes and 90° phase differences ($-90^\circ$ ($-i$) for the 3rd harmonic, while $+90^\circ$ ($+i$) for the intermodulation) to maintain them be completely coupled to $P_4$ isolated from the incident port without any power reflection. Therefore, the signals generated from $D_1$ and $D_2$ are totally delivered to the isolated port of the dual-mode hybrid coupler, which can be calculated as shown below.

$$V_{\text{iso}}^* = -i\frac{a_3V_{\text{IN}}^3}{2\sqrt{2}}\cos3\omega_gt \quad (10)$$

$$V_{\text{iso}}^* = i\frac{25a_3V_{\text{IN}}^5}{32}(\cos\omega_{\text{IM1}}t + \cos\omega_{\text{IM2}}t) \quad (11)$$

FIGURE 3. Phase differences and power magnitudes of the ADS simulation. (a, c) 3rd harmonic and (b, d) intermodulation.

FIGURE 4. (a) two-tone and (b) single-tone signals as well as the intermodulation and 3rd harmonic through the hybrid coupler.

The single-tone and two-tone signals as well as 3rd harmonic and intermodulation spectrums delivering through the dual-mode hybrid coupler can be observed in Fig. 4, which guides how to perform the experimental validation in next section.

Furthermore, to evaluated the different diode influence of the balanced intermodulation generations, an SMS7630 diode is selected as a comparative simulation experiment for both the 3rd harmonic and intermodulation through the hybrid coupler. The ADS parameters settings of SMS7630 are identical with ones of HSM82860, which is detailed in the TABLE 1. The 3rd harmonic and intermodulation generated from $D_1$ and $D_2$ for the diodes of SMS7630 and HSM82860 are provided co-located in Fig. 3c and 3d. From the simulations, it is found that SMS7630 outperforms over the low power ranges for matter the 3rd harmonic ($-10$ to $-2$ dBm) and intermodulation ($-10$ to $-4$ dBm), while the HSM82860 outperforms over the mid power range for matter the 3rd harmonic ($-2$ to $+10$ dBm) and intermodulation ($-4$ to $+10$ dBm). Therefore, diodes can be carefully selected for its specific applications.

III. EXPERIMENTAL RESULT

The proposed intermodulation generator is designed at $\omega_0 = 2$ GHz in ADS and fabricated on a low-loss 20-mil RO4350B substrate. Two categories of Schottky diodes SMS7630 and HSM82860 are employed as $D_1$ and $D_2$ for high-efficiency balanced intermodulation generations.

As depicted in Fig. 5a, another 2-GHz hybrid coupler is used as a two-tone signal power combiner, whose coupled port is matched to a 50-Ω terminal. A signal generator AV1441A and a vector network analyzer AV3656A (alternative signal generator) are utilized to generate the two tones at $\omega_1 = 1.98$ GHz and $\omega_2 = 2.02$ GHz, respectively, whose output ports are directly connected to the input ($P_1$) and isolated ($P_4$) ports of the two-tone power combiner (i.e., 2-GHz hybrid coupler).

Therefore, the two tones are generated at the direct ($P_2$) port. When two tones interrogate at the input ($P_1$) port, a spectrum analyzer is employed to readout the intermodulation at the isolation port ($P_4$) of hybrid coupler. Since intermodulation generations at $\omega_{\text{IM1}}$ and $\omega_{\text{IM2}}$ have equal power magnitudes, only the lower frequency ($\omega_{\text{IM1}}$) is considered and measured during the experiment. The intermodulation generation from different Schottky diodes of SMS7630 and HSM82860 over the power range from...
-10 dBm to +10 dBm can be observed in Fig. 6. Since the signal generator AV1441A and the vector network analyzer AV3656A cannot cover 3rd harmonics (3ω₀ = 6 GHz), only the intermodulation from the isolation port (P4) is measured by compared to the simulated 3rd harmonics.

It is indicated that a good agreement between the simulated and measured results can be achieved from both the Schottky diodes of SMS7630 and HSMS2860. For the meantime, the intermodulation outperforms 3rd harmonics (simulated) over low power range no matter the Schottky diode SMS7630 (−10−0 dBm) or HSMS2860 (−10−3 dBm). However, for the diode of HSMS2860, the power level difference is very small, which demonstrations that the power conversion efficiency of both the intermodulation and 3rd harmonics are kept with similar values. Therefore, for same power incidence (single or two tones), the intermodulation generator presented in this article can have absolutely superiority when transferring from the terminal to the base station.

**IV. CONCLUSION**

An intermodulation generator is designed and presented with integration of a dual-mode hybrid coupler and two identical diodes, whose connection polarities to the direct and coupled ports of the hybrid coupler are opposite for a rapid realization of balanced intermodulation generation. In consequence of the superior coupling characteristics of hybrid coupler, it can distribute incident tow tones to the direct and coupled ports evenly, and deliver the balanced intermodulation generations to the isolation port highly insulated from its incident port.

To enhance the intermodulation generations, two identical quarter-wavelength shorted stubs at fundamental frequency are implemented by suppressing the second-order spectrums. Both theoretical analysis and experiments validate that the presented intermodulation generator can outperform the 3rd harmonic generator, and highly isolate its incidences (the two tones) and outputs (the intermodulation generations) for its future high-isolation wireless sensing applications.

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