Design of a Compact Harmonic Transponder Based on Quarter-Wavelength Impedance Transformers

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Abstract — In this paper, the optimised design of a fully passive harmonic transponder is presented. The proposed harmonic transponder is based on the use of quarter-wavelength impedance transformers. Two quarter-wavelength transformers are used to control the fundamental frequency and the harmonic in a traditional harmonic transponder. By adding one additional quarter-wavelength transmission line at the fundamental frequency and another at the harmonic (or one-eighth wavelength at the fundamental frequency), the input and output can share one port for communications. The device has very a small circuit size and high performance. Compared to a typical passive harmonic transponder with two independent antennas, the proposed harmonic transponder can reduce the limitation of the antenna design without increasing the circuit area and is beneficial for designers to improve the performance of the antenna. Measurement results show that a conversion loss of 15 dB can be achieved at an input power of -25 dBm and an operating frequency of 2.4 GHz. The circuit size is only 10 mm × 12 mm.

Keywords — harmonic transponder, impedance transformer, Schottky diode.

1. Introduction

With the popularization of the Internet of things (IoT) and wireless sensor networks (WSNs) in life, the massive deployment of electronic devices has made the problem of co-channel interference more and more serious. In this scenario, harmonic transponders have received more attention due to their inherent high robustness to interference from environmental reflection (clutter). This kind of clutter usually exists at the fundamental frequency [1]. By using harmonics for communications, the clutter at the fundamental frequency can be easily filtered out. A harmonic transponder has been widely used as beacons for harmonic radars, such as collision avoidance system [2], disaster victim detection [3] and tiny tracker [4] to avoid strong harmful reflection. Recently, passive wireless sensors based on harmonic transponders have been reported for backscattering communications at extremely low power levels [5-6].

As shown in Fig 1, a traditional passive harmonic transponder includes a pair of antennas for receiving and transmitting and a nonlinear device (usually a diode) in the receiver to generate harmonics. The base station sends out a signal at the fundamental frequency, which will be received by the receiver antenna with a harmonic transponder. This transponder will generate the second harmonic and send it back using a transmit antenna. The 2nd harmonic signal can then be captured by the base station. If a resonant type of antenna is used, the transmitting/receiving antenna working at the
fundamental frequency may also resonate at the 2nd harmonic frequency. To achieve good performance, high isolation between the transmitting and receiving antennas is needed, limiting the flexibility of antenna design. A diplexer-based single-port harmonic transponder combines the input and output ports while providing significant isolation [7]. The diplexer is based on the half-wavelength open-circuited microstrip line resonator design, which offers two passbands (at the fundamental frequency and 2nd harmonic) and high isolation between ports. The single-port harmonic transponders can simply use a dual-band antenna to replace traditional Tx and Rx antenna pairs, which makes dual-frequency omnidirectional antennas with higher radiation efficiency and gain possible.

In this work, an optimised design of a fully passive harmonic transponder using quarter-wavelength impedance transformers is proposed and analysed. Quarter-wavelength transformers were utilised to control the fundamental signal and the harmonic. A one-eighth transmission line is added to effectively act as a duplexer. The transponder has a small size with high performance while enabling the input and output to share one port for communication. The circuit size is further reduced by using lumped-element inductors. The proposed harmonic transponder can reduce the limitation of the antenna design without increasing the circuit area and is beneficial for designers to improve the performance of the antenna. The rest of the paper is organized as follows: Section II proposes the working principle of the proposed harmonic transponder with a single port. Section III includes two parts: the first part details the design example and simulation results; the second part shows the measurement setup and experimental results. Finally, the conclusion is presented in Section IV.



Fig. 1. Block diagram of a harmonic transponder system with two-ports and one-port topologies.



Fig. 2. Simplified schematic of the traditional fully passive harmonic transponder with two ports.



Fig. 3. Simplified schematic of the proposed harmonic transponder with a single port by adding a one-eighth wavelength transmission line.

1. Topology and Theoretical Analysis

The schematic of a typical passive harmonic transponder with two ports is shown in Fig. 2. The inherent nonlinearity of the diode will cause the input waveform at the fundamental frequency to be distorted, resulting in higher-order harmonics. To enhance the second harmonic conversion efficiency of the diode, a short-circuited and an open-circuit quarter-wavelength stubs (named as TL1 and TL2) at fundamental frequency $f\_{0}$ are placed on the two sides of the diode, respectively. The $λ/4$ short-circuited stub TL1 at the input side operates as an open circuit at the fundamental frequency. It allows the injected fundamental signal to reach the diode. But it acts as a short circuit at the 2nd harmonic frequency, to be discussed in more detail in the next paragraph. On the other side, the $λ/4$ open-circuit stub TL2 short-circuits the fundamental frequency without affecting the 2nd component. This is because the open-circuit quarter-wavelength stub at $f\_{0}$ is half-wavelength long and has an input impedance of infinity at the 2nd harmonic.

To enable the transponder's input and output sharing one port without using a duplexer, a $λ/8$ transmission line TL4 (at $f\_{0}$) is added between the input impedance matching network and the $λ/4$ short-circuited stub TL1. The transponder's output is connected to point A by a quarter-wavelength transmission line TL3 (at $f\_{0}$), as shown in Fig. 3. Like the traditional topology, the $λ/4$ short-circuited stub TL1 at the input side makes point B open circuit at the fundamental frequency and short-circuited at the 2nd harmonic frequency. The added transmission line between point A and B is λ/8 long at $f\_{0}$ and quarter-wavelength long at $2f\_{0}$. The 2nd harmonic frequency that was originally short-circuited at point B will see an open circuit at point A. That is, at the 2nd harmonic frequency, this λ/8 transmission line TL4 makes the input impedance infinity, seeing from Point A towards the diode. But it will only cause some phase changes with very little insertion loss to the fundamental frequency, hence it has very little effect on the operation of the diode.

The quarter-wavelength open-circuit stub TL2 at the output side makes point C short-circuited at the fundamental frequency and open circuit at the 2nd harmonic frequency. Thanks to the λ/4 transmission line TL3 (at $f\_{0}$) between point A and C, at the fundamental frequency, the input impedance seeing from point A to point C through TL3 will be infinity. No power at the fundamental frequency will go through this transmission line to the output side of the diode. Because this λ/4 transmission line TL3 (at $f\_{0}$) is half-wavelength long at the second harmonic, this transmission line has no effect on the transmission of the second harmonic from the output side of the diode to the port. Put it in another way, for the second harmonic, the output impedance seen at the output of the diodes, will be the same as the input impedance to the input port seen at Point A. Both an input matching network (I.M.N.) and an output matching network (O.M.N.) can be added to optimise the circuit performance further as shown in Fig. 3.

In general, the signal at the fundamental frequency injected from the input port only passes through the λ/8 transmission line TL4 and reaches the diode. It will not reach the output of the diode through TL3 directly as discussed above. On the contrary, the second harmonic from the diode output can pass through the added quarter-wavelength transmission line TL3 and reaches the input port. The harmonic will not be injected into the diode again. The proposed harmonic transponder enables the input and output to share one port for communication without affecting each other.

1. The proposed harmonic transponder
2. Circuit Design

Design of the proposed fully passive harmonic transponder is presented in this section. A traditional harmonic transponder working at the frequency of 2.4 GHz with two ports is designed first. As shown in the circuit diagram in Fig. 4, the harmonic transponder consists of an input matching network, a Schottky diode and an output matching network. $C\_{1}$ and $C\_{2}$ as DC blocking capacitors are placed at the input and output ports. A Schottky barrier diode (SBD) SMS7630 with a low threshold voltage from Skyworks is chosen. Both matching networks are based on a single inductor to compensate for the junction capacitance $C\_{j}$ and package capacitance $C\_{p}$ of the diode, as shown in Fig. 5. The inductor is intended to resonate with the parasitic capacitance of the diode at the operating frequency.

Using a single inductor instead of a complicated matching circuit can reduce the loss from impedance matching and minimize the size of the circuit board [8]. The performance of the proposed harmonic transponder was simulated using Advanced Design System (ADS) with a nonlinear diode SPICE model with parasitic. Fig. 6 depicts the reflection coefficient of the proposed harmonic transponder with two ports working at 2.4 GHz from large-signal S-parameter simulation. The value is lower than -15 dB for both $S\_{11}$ (red line) at 2.4 GHz and $S\_{22}$ (blue line) at 4.8 GHz, which proves this technique can provide good impedance matching.



Fig. 4. Schematic of a passive harmonic transponder with two ports.



Fig. 5. Equivalent circuit of a diode.



Fig. 6. Comparison of simulated S-parameters of the harmonic transponders with two-ports and one-port topologies.

The proposed harmonic transponder with a single port based on using quarter-wavelength impedance transformers is shown in Fig. 7. In order to eliminate the influence of inductors in the matching networks, the length of the quarter-wavelength transmission line TL3 (at $f\_{0}$) and λ/8 transmission line TL4 (at $f\_{0}$) have been re-optimized. After optimisation, *S11* (black line) is better than -10 dB at both 2.4 GHz and 4.8 GHz, as shown in Fig. 7, when the input power is -25 dBm. Fig. 8 shows the power conversion loss $CL$ of the proposed harmonic transponder with a single port and a traditional harmonic transponder with two ports from harmonic balance simulation using ADS. The power conversion loss is given by:

$CL (in dB)=P\_{f\_{0}}\left(dBm\right)-P\_{2f\_{0}}\left(dBm\right)$ (1)

where $P\_{f\_{0}}$ is the incident power at the fundamental frequency in dBm and $P\_{2f\_{0}}$ is the output power of the harmonic transponder at the 2nd harmonic frequency. The red line shows the power conversion loss of the harmonic transponder with two ports and the blue line shows the one with a single port. When the input power range is between -30 dBm and -10 dBm, there is no significant difference between them.



Fig. 7. Schematic of the proposed passive harmonic transponder with a single port.



Fig. 8. Comparison of simulated conversion loss of the harmonic transponders with two-ports and one-port topologies.

1. Experimental Results

 For evaluating the performance of the proposed harmonic transponder with a single port based on using quarter-wavelength impedance transformers, a prototype is fabricated on Rogers RO4003C substrate with a relative permittivity of 3.55 and thickness of 1.52 mm. The PCB layout of the proposed passive harmonic transponder and a photograph of the fabricated prototype is shown in Fig.9. The size of the active area is only 12 mm long and 10 mm wide.

In the measurement, the transponder is operated at $f\_{0}$ = 2.4 GHz and $2f\_{0}$ = 4.8 GHz. Since the proposed harmonic transponder uses the same port for input and output signals, to facilitate measurement, a -3 dB broadband Wilkinson power divider was used in the experimental setup. The proposed harmonic transponder is connected to the input port (port 1) of the Wilkinson power divider. An RF signal generator and a spectrum analyser were connected to the two output ports (port 2 and port 3) of the power divider, respectively. The RF power at the fundamental frequency was generated by the RF signal generator. Half of the power will go through the power divider to the harmonic transponder at port 1, and another half power will be absorbed by isolation resistor in the Wilkinson power divider. Similarly, half of the 2nd harmonic power generated by the harmonic transponder will be delivered to the spectrum analyser at port 3. Another half is absorbed by the equivalent input impedance of the signal generator.



 (a) (b)

Fig. 9. (a) Layout of proposed passive harmonic transponder. (b) Fabricated passive harmonic transponder.



Fig. 10. Simulated and measured conversion loss of proposed harmonic transponder, and photo of the fabricated prototype.

The blue line in Fig. 10 shows the measured conversion loss of the proposed harmonic transponder. The insertion loss of the power divider and the loss of cables and connectors have been taken into account in the measurement. It can be observed that the measured results agree well with the simulated ones. When the input power is between -30 dBm and -10 dBm, the transponder can achieve a conversion loss of no more than 20 dB. And the proposed harmonic transponder has stable conversion loss in a dynamic input power rang of at least 15 dB (from -25 dBm to -10 dBm).

Table 1 compares the performance of the proposed passive harmonic transponder with previous works. Since the quarter-wavelength impedance transformer network replaces the originally required diplexer, the proposed design is the smallest among them in comparison with the circuit size of a single-port transponder. And lower conversion loss is achieved under the input power of -25 dBm, which proves that the proposed structure does not add additional power loss.

Table. 1. Comparison with previous works

|  |  |  |  |
| --- | --- | --- | --- |
| Reference | [6] 2017 | [7] 2019 | This work |
| Type | Passive | Passive | Passive |
| Frequency | 1.2 GHz | 3.5 GHz | 2.4 GHz |
| Harmonic | Second | Second | Second |
| No. of port | Two | One | One |
| Board size | 8 $×$ 28 mm2 | 24 $×$ 24 mm2 | 10 $×$ 12 mm2 |
| Conversion loss @-25 dBm | 26.5 dB | 17 dB | 15 dB |

1. Conclusion

 This paper has reported a fully passive harmonic transponder with a single port for both input and output. Thanks to the quarter-wavelength impedance transformer networks added to the device, the transponder has a very small size and can achieve better performance while enabling input and output to share one port for communications. The proposed harmonic transponder can provide great flexibility for the antenna design, which is beneficial for designers to improve the performance of the antenna and the overall performance of transponders. Since quarter-wavelength impedance transformer networks are used to replace a diplexer which would be needed otherwise, the proposed single-port harmonic transponder has better tolerance for operation frequency range than a single-port harmonic transponder based on a resonant diplexer. And transmission line based impedance transformer networks can reduce the area occupied by the PCB board by simply folding. For evaluating the performance, a harmonic transponder based on an SMS7630 Schottky diode working at the frequency of 2.4 GHz has been designed. The circuit is very compact. The simulated and measured results show the effectiveness of the proposed topology. A conversion loss of 15 dB has been achieved at an input power of -25 dBm.

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