Sensitivity of MEMS microwave power sensor with the length of thermopile based on Fourier equivalent model*

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Abstract: A Fourier equivalent model is introduced to research the thermal transfer behavior of a terminating-type MEMS microwave power sensor. The fabrication of this MEMS microwave power sensor is compatible with the GaAs MMIC process. Based on the Fourier equivalent model, the relationship between the sensitivity of a MEMS microwave power sensor and the length of thermopile is studied in particular. The power sensor is measured with an input power from 1 to 100 mW at 10 GHz, and the measurement results show that the power sensor has good input match characteristics and high linearity. The sensitivity calculated from a Fourier equivalent model is about 0.12, 0.20 and 0.29 mV/mW with the length at 40, 70 and 100 μm, respectively, while the sensitivity of the measurement results is about 0.10, 0.22 and 0.30 mV/mW, respectively, and the differences are below 0.02 mV/mW. The sensitivity expression based on the Fourier equivalent model is verified by the measurement results.

Key words: MEMS; thermopile; microwave power; sensitivity

DOI: 10.1088/1674-4926/32/7/074009 **EEACC:** 2575; 8460

1. Introduction

Thermocouple-based power sensors have been one of the most widely used tools for microwave power detection. The operation principle of these sensors is based on the transformation of microwave energy into heat energy by the absorbing terminal resistors and on the measurement of the temperature difference between the hot junction and the cold junction[1, 2]. In our previous work, some research on optimization of this structure has been reported. In Ref. [3], GaAs substrate was chosen, and four different types of CPW were designed, so as to improve the sensitivity. The sensitivity is the ratio of the output voltage to the input microwave power; in Ref. [4], a SPICE model was introduced to simulate the temperature distribution, then an amplification system was presented to obtain high sensitivity; in Ref. [5], the transient response of the sensor was investigated.

However, up to now, little work that discusses the relationship between the sensitivity and the length of these sensors has been reported. The length of the thermocouples is one of the most important factors to influence the sensitivity. In this work, a Fourier equivalent model is introduced to research the thermal transfer behavior of a terminating-type MEMS microwave power sensor. The length of the thermopile has been chosen as an independent variable to research the relationship with the sensitivity of the power sensor. By varying the length, different sensitivities are obtained, and the sensitivity expression based on the Fourier equivalent model is tested against the measurement.

2. Principle and model

The structure of the MEMS microwave power sensor is shown in Fig. 1(a). The basic elements of this power sensor are the CPW transmission lines, a couple of absorbing terminal resistors, a thin-film thermopile and DC output pads. The CPW is designed to have a characteristic impedance of 50 Ω and to be the signal input port. The terminal resistors absorb the microwave power and convert it into heat. Then, the thermopile measures the temperature difference and generates a

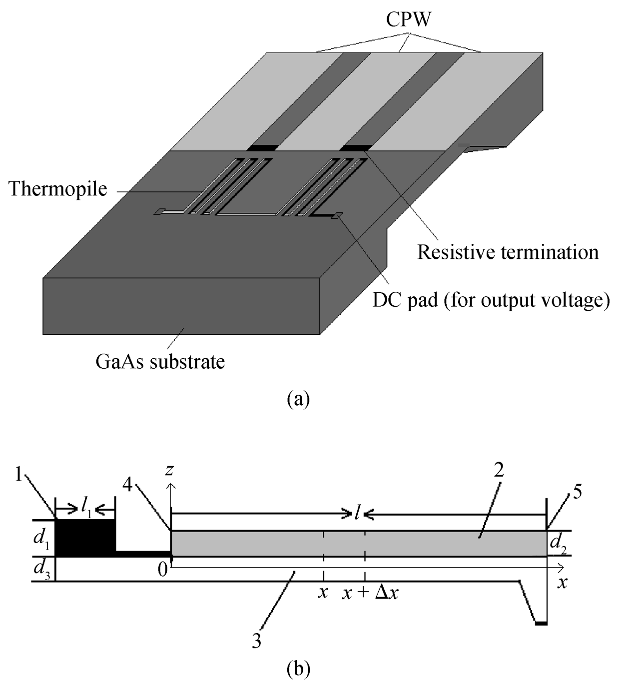

Fig. 1. (a) Structure of the MEMS microwave power sensor. (b) Cross section view of the microwave sensor. 1: terminal resistor; 2: thermocouple; 3: GaAs substrate; 4: hot junction; 5: cold junction.

* Project supported by the National Natural Science Foundation of China (Nos. 61076108, 60976094, 60676043) and the National High Technology Research and Development Program of China (No. 2007AA04Z328).

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Received 25 January 2011, revised manuscript received 24 February 2011

DC voltage based on the Seebeck effect.

The output voltage V_{out} and the sensitivity S_{total} of the power sensor are expressed, respectively, as

$$V_{out} = a\sum_{i}^{N}(T_h - T_c), \quad (1)$$

$$S_{total} = V_{out}/P_{total}, \quad (2)$$

where a is the Seebeck coefficient, N is the number of thermocouples, T_h and T_c are the temperatures of the hot and cold junction, and P_{total} is the total microwave power provided to the CPW line. To simplify the model, the thermopile and the substrate are regarded as one material with some equivalent parameters, and the equivalent thermal conductivity λ_e can be defined as[5]

$$\lambda_e = \frac{\lambda_3 d_3 + \lambda_2\dfrac{d_2}{2}}{d_e} = \frac{\lambda_3 d_3 + \lambda_2\dfrac{d_2}{2}}{d_3 + \dfrac{d_2}{2}}, \quad (3)$$

where $\lambda_2 = (\lambda_n + \lambda_p)/2$ is the average thermal conductivity, λ_n and λ_p are the thermal conductivity of GaAs and Au, respectively, λ_3 is the thermal conductivity of the GaAs substrate, $d_e = d_3 + d_2/2$ is the equivalent thickness of the thermocouple and, as shown in Fig. 1(b), the parameters d_2 and d_3 are the thickness of the thermocouple and GaAs substrate, respectively.

As the coordinate system shown in Fig. 1(b), the heat exchange $Q_1(T)$ from x to $x + \Delta x$ by means of the thermal conduction is expressed as

$$Q_1(T) = \mathrm{d}Q_{out} - \mathrm{d}Q_{in} = A\frac{\partial q_x}{\partial x}\Delta x = -\lambda_e w d_e \frac{\mathrm{d}^2 T}{\mathrm{d}x^2}\Delta x, \quad (4)$$

where Q is the heat-flux, A is the cross-sectional area, w is the width of the thermocouple, q_x is the heat flux density, and T is the temperature of the thermocouple. The heat exchange $Q_2(T)$ by means of the convective heat transfer and the heat exchange $Q_3(T)$ by means of the radiant heat transfer from the lower and upper layers is expressed as, respectively,

$$Q_2(T) = 2hw(T - T_0)\Delta x, \quad (5)$$

$$Q_3(T) = w\sigma_b(\varepsilon_e + \varepsilon_s)(T^4 - T_0^4)\Delta x, \quad (6)$$

where $\varepsilon_e = (\varepsilon_n + \varepsilon_p)/2$ is the average emissivity, ε_n, ε_p and ε_s are the emissivity of GaAs, Au and the substrate layers, respectively, h is the convection coefficient, σ_b is the Stefan–Boltzmann constant, and T_0 is the ambient temperature. From Eqs. (4)–(6), the stationary Fourier heat equation of the thermocouple can be expressed as[2, 6]

$$-\lambda_e d_e \frac{\mathrm{d}^2 T}{\mathrm{d}x^2} + 2h(T - T_0) + \sigma_b(\varepsilon_e + \varepsilon_s)(T^4 - T_0^4) = 0, \quad (7)$$

as $T_h - T_0 \ll T_0$, $T^4 - T_0^4 \approx 4T_0^3(T - T_0)$, Equation (7) is simplified as

$$-\lambda_e d_e \frac{\mathrm{d}^2 T}{\mathrm{d}x^2} + H(T - T_0) = 0, \quad (8)$$

where $H = 2h + 4\sigma_b(\varepsilon_e + \varepsilon_s)T_0^3$, and boundary conditions for Eq. (8) are

$$-\lambda_e \left.\frac{\mathrm{d}T}{\mathrm{d}x}\right|_{x=0} = q_{in}, \quad T|_{x=l} = T_0, \quad (9)$$

where q_{in} is the heat flux density from terminal resistor to the hot junction. From Eqs. (1), (2), (8) and (9), the sensitivity S of the thermopile is obtained as

$$S = \frac{V_{out}}{q_{in}} = (a_n - a_p)\frac{N}{\lambda_e p}\tanh(pl), \quad (10)$$

where $p = \sqrt{\frac{H}{\lambda_e d_e}}$, a_n and a_p are the Seebeck coefficients of GaAs and Au, respectively, and l is the length of the thermocouple. In Eq. (9), the value of the heat flux density q_{in} can be defined as

$$q_{in} = \frac{1}{2}\frac{Q_{total}}{A'} = \frac{1}{2}\frac{\beta P_{total}}{A'} = \frac{1}{2}\frac{\beta P_{total}}{W d_e'}, \quad (11)$$

where Q_{total} is the total heat-flux. It distributes around the terminal resistor and half of the heat-flux transfer to the hot junction, $d_e' = d_1 + d_3$ is the equivalent thickness of terminal resistor, d_1 is the thickness of terminal resistor, β is the total absorbing efficiency, and A' is the effective cross-sectional area of the heat-flux and we assume that it distributes evenly on this area. According to Ref. [4], the effective value of the area A' (the effect width W) is accepted. From Eqs. (2), (10) and (11), the expression for total sensitivity and output voltage of the sensor can be obtained, respectively,

$$S_{total} = \frac{(a_n - a_p)\beta N \tanh(pl)}{2\lambda_e p W d_e'} \quad (\mathrm{mV/mW}), \quad (12)$$

$$V_{out} = P_{total} S_{total}. \quad (13)$$

The materials for the positive and negative conductors of the MEMS power sensor are Au and GaAs. The parameter values of the sensor are shown in Table 1.

According to Eq. (12), the relationship between the sensitivity of the MEMS power sensor and the length of thermopile is shown in Fig. 2. For the shorter length, the sensitivity increases rapidly with the length and has good linearity. And with increasing length, the growth rate of the sensitivity slows down. When the length is more than 5 mm, the linearity of the sensitivity becomes bad. It increases slowly until reaching a saturation state. The longer the length, the greater the sensitivity, but the thermal time constant increases faster[5] and the noise becomes larger[7]. Meanwhile, the size of the device becomes much greater. So the trade-offs have to be weighed among the sensitivity, the noise, the thermal time constant and the chip size. The length should not be too long or too short. In order to obtain the highest growth speed of the sensitivity while maintaining a small chip size, the values of the length for fabrication are chosen as follows: 40, 70 and 100 μm. According to Eq. (13), the sensitivity calculated from the Fourier equivalent model is about 0.12, 0.20 and 0.29 mV/mW at 40, 70 and 100 μm, as shown in Fig. 3, respectively, and it has good linearity.

Table 1. Parameter values.

Element	Parameter	Value
Thermal conductivity (Au)	λ_p	315 W/(m·K)
Thermal conductivity (GaAs)	λ_n	46 W/(m·K)
Thermal conductivity (GaAs substrate)	λ_3	46 W/(m·K)
Emissivity (Au)	ε_p	0.02
Emissivity (GaAs)	ε_n	0.3
Emissivity (substrate)	ε_s	0.3
Seebeck coefficients (Au)	a_p	1.7 μV/K
Seebeck coefficients (GaAs)	a_n	173.42 μV/K
Thickness of terminal resistor	d_1	2 μm
Thickness of thermocouple	d_2	2 μm
Thickness of GaAs substrate	d_3	20 μm
Length of thermocouple	l	40, 70 and 100 μm
Number of thermocouples	N	14
Stefan-Boltzmann constant	σ_b	5.67×10^{-8} W/(m^2·K^4)
Convection coefficient	h	1 W/(m^2·K)
Total absorbing efficiency	β	0.88
Effect width of the heat-flux q_{in}	W	316 μm
Ambient temperature	T_0	300 K

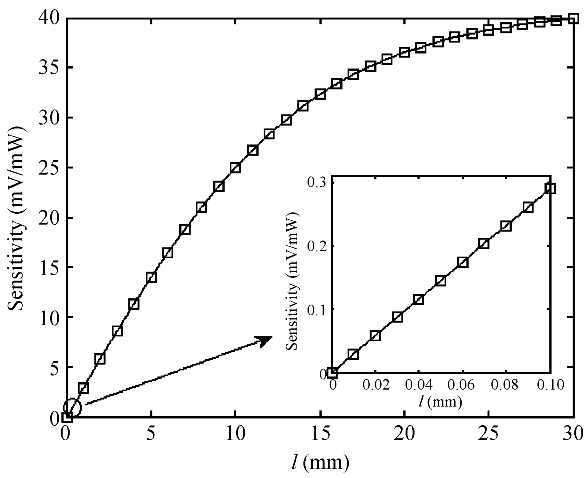

Fig. 2. Sensitivity versus length l.

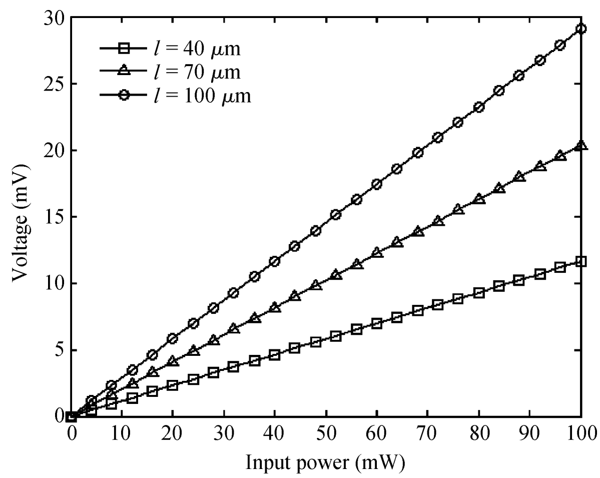

Fig. 3. Output voltage versus input power characteristics.

3. Design and fabrication

The fabrication of this power sensor is compatible with the GaAs MMIC process[8]. Bulk micromachining technology on GaAs is used to define the membrane structure. The coplanar waveguide is a fundamental and important element for MMICs due to its ease of mounting active devices. The process steps of the power sensor are described briefly as follows:

(1) The thickness of the GaAs supporting layer is 500 μm. AlGaAs thin film and GaAs are epitaxially grown. AlGaAs thin film is used as the etch-stop layer. The n^+ GaAs is made of a 2500 Å thick epitaxial layer for one leg of the thermopiles with a Seebeck coefficient of 173.42 μV/K.

(2) The AuGeNi/Au layer is sputtered for the second leg of the thermopiles by using a lift-off process by evaporating the 500/2200 Å thickness. The role of the AuGeNi/Au layer is to form ohmic contact with the n^+ GaAs to reduce the thermal noise[9].

(3) The terminal resistor is made by using a lift-off process by depositing a TaN layer with a square resistance of 25 Ω/□. The width of the load resistor is 14.5 μm since the slot of CPW is fixed 58 μm.

(4) A 500/1500/300 Å Ti/Au/Ti seed layer is sputtered and patterned. The role of the Ti/Au/Ti seed layer is to enhance the adhesion between Au and the substrate and to prevent Au from giving off when bonding.

(5) After removing the top Ti layer, the transmission lines of CPW are formed through electroplating a 2 μm thick Au layer.

(6) The GaAs substrate is subtracted thin to 100 μm.

(7) The GaAs substrate is etched back to the AlGaAs layer.

The process steps of the power sensor are shown in Fig. 4. The SEM photo of the power sensor and the photo with different lengths are shown in Fig. 5.

4. Experimental results

The sensors are measured using an Agilent E8257D PSG analog signal generator, an Agilent 8719ES network analyzer and a Cascade Microtech 1200 probe station. The return loss

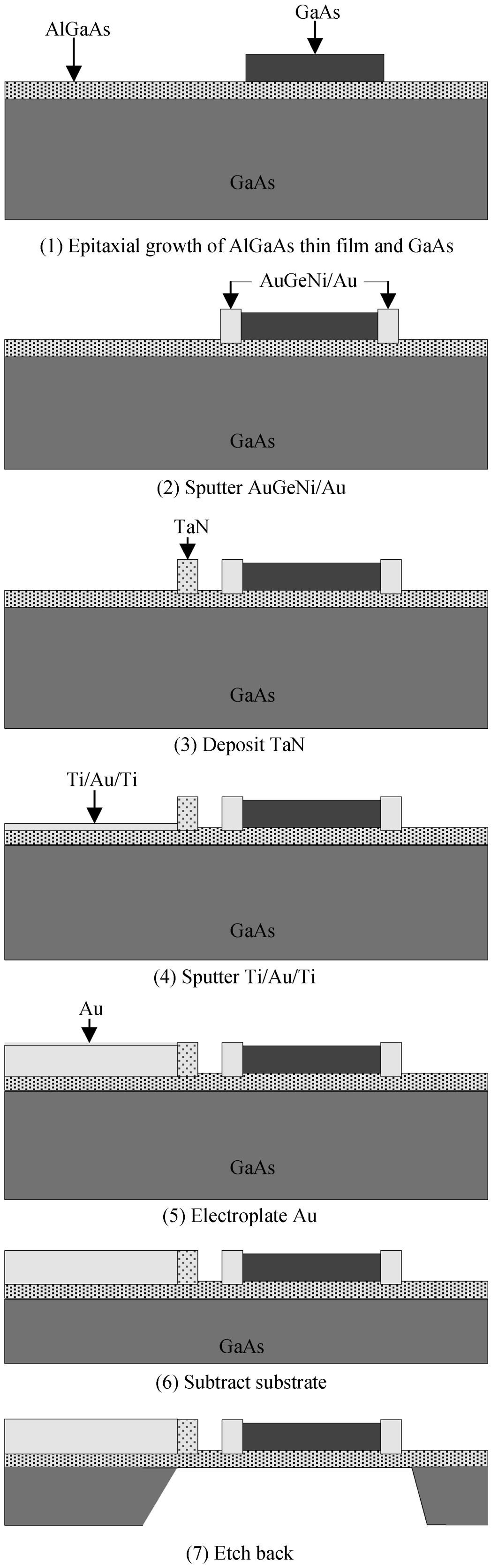

Fig. 4. Process steps during fabrication.

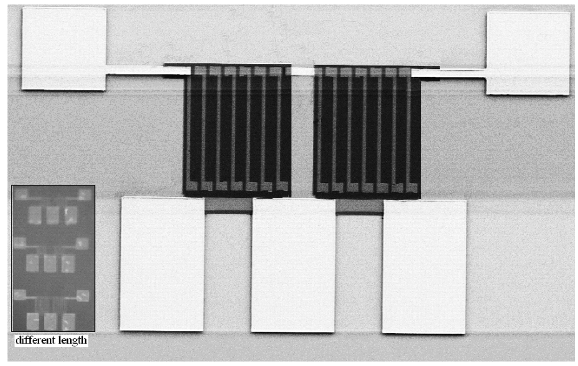

Fig. 5. SEM photo of the power sensor.

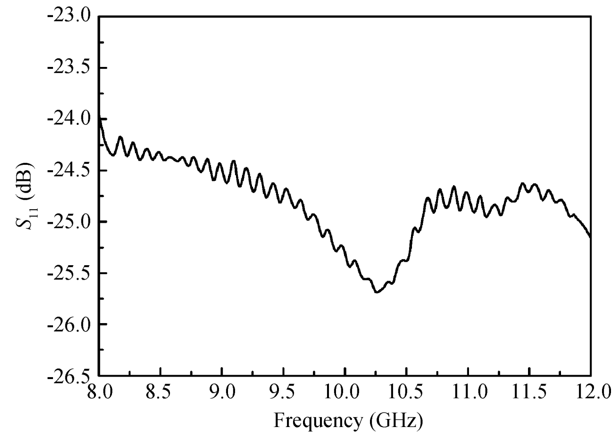

Fig. 6. Measured return loss of the microwave sensor.

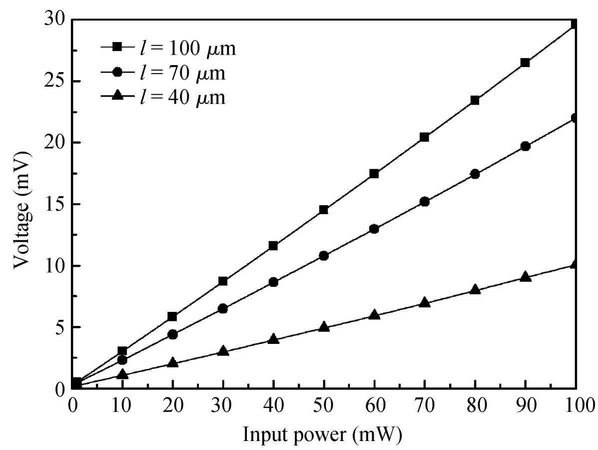

Fig. 7. Measured output voltage versus input power characteristics.

used to determine the input mismatch error is shown in Fig. 6. The measurement results include the parasitic of the MEMS power sensor. The return loss of the sensor is between –24 and –26 dB over the entire frequency range, and the corresponding reflection coefficient Γ is between 0.0631 and 0.0501. It reflects that the power sensor has a good input match characteristic.

In order to measure the sensitivity of the power sensor, the microwave signals applied to the power sensor are in the range of 1 to 100 mW at 10 GHz, and the output voltage is recorded as shown in Fig. 7. The length is designed to be 40, 70 and 100 μm, respectively, and the number of thermopiles is designed in 14 pairs. The measurement results show that the power sensor has good linearity. The sensitivity is about 0.10, 0.22 and

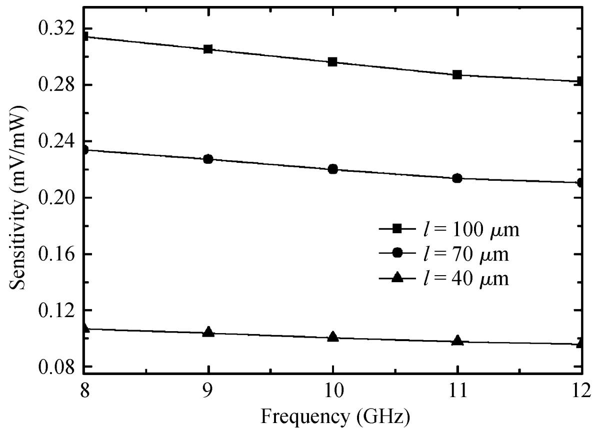

Fig. 8. Measured frequency dependence of the sensitivity.

0.30 mV/mW with the length l at 40, 70 and 100 μm, respectively, compared with the Fourier equivalent model, as shown in Fig. 3, the sensitivity is about 0.12, 0.20 and 0.29 mV/mW at 40, 70 and 100 μm, respectively, and the differences are below 0.02 mV/mW. The slope of the measurement curves increases gradually with the length range from 40 to 100 μm. However, compared with the length from 70 to 100 μm, the increased amount of the length from 40 to 70 μm becomes more obvious. This means that with the length increasing, the growth rate of the sensitivity slows down. In addition, the measurement results are very similar to the simulation results in the Fourier equivalent model.

As shown in Fig. 8, the microwave signals applied to the power sensor are in the range of 8 to 12 GHz at 100 mW, and the frequency dependences of sensitivity with the length at 40, 70 and 100 μm are measured. Figure 8 shows that the sensitivity decreases with the frequency, and the frequency-dependent losses of the sensitivity increase with the length of the thermopile. Because the thermopile is expected to absorb the heat energy from the load resistors, rather than the electromagnetic field energy, the electromagnetic coupling loss exists between the load resistors and the thermopile[10]. In addition, as a resistance increase in the load resistors due to the skin effect, the impedance change of the load resistors due to its reactive component and the shunting effect of the thermopile due to the capacitive coupling and the inductive coupling between the load resistors and the thermopile, the sensitivity decreases with frequency. Furthermore, as the parasitic capacitance and inductance are increasing with the length of the thermopile, the frequency-dependent losses of sensitivity increase gradually with the length.

5. Conclusion

A Fourier equivalent model has been introduced to research the thermal transfer behavior of a terminating-type MEMS microwave power sensor in this paper. The length of the thermopile has been chosen as an independent variable to research the relationship with the sensitivity of the power sensor. Then the simulation results and measurement results of the sensitivity are given. The experimental results show that the power sensor has good input match characteristics and good linearity, and the sensitivity expression based on the Fourier equivalent model is tested against the measurement.

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