A Calibration Method of a Range Finder With a Six-Port Network

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***Abstract*—A calibration method is proposed for a range finder with a six-port phase frequency discriminator. Calibration equations are derived that include phase errors resulting from both the imperfections in a six-port network and the different diode characteristics. The equations allow a simple and accurate calibration of the range finder with the six-port network. Calibration parameters are calculated from dc outputs, which are measured as the output frequency is varied. The maximum error of a distance measurement from 0.5 to 3 m is $\sim 2\%$.**

***Index Terms*—Distance measurement, radar calibration, radar sensor, six-port network, six-port phase frequency discriminator.**

I. Introduction

A SIX-PORT phase frequency discriminator, having two inputs and four outputs, consists of passive devices. The six-port circuit was developed in the 1970s for accurate automated measurements of complex reflection coefficients [1]. The complex reflection coefficients are obtained as dc output voltages at the output ports [2]. This also applies to short distance radar systems, for example, an autonomous cruise control system [3] or a high-precision ranging system [4].

In general, a six-port network is calibrated with known test devices such as a sliding load [2]. However, this is not feasible for a radar sensor, as the calibration requires a great amount of time, and it is necessary to calibrate each port with multiple standards.

Tatu [5] describes the complex reflection coefficient Γ using four six-port dc output voltages with

$$\Gamma = (V_3 - V_4) + j(V_5 - V_6). \tag{1}$$

Previous studies assumed several important factors in their calibrations. There are that the dc offset voltage in each port is equal to zero, that all ports are matched with high accuracy, that the diode characteristics are identical, and that the errors in the passive components do not affect the calibration parameters. However, a dc offset, especially a dynamic dc offset, cannot be perfectly canceled out. The mismatches of the diode characteristics in addition to the phase errors in a six-port network also cannot be neglected during the calibration of a radar sensor that requires high accuracy. Thus, the previous methods cannot be successfully used in the range finder.

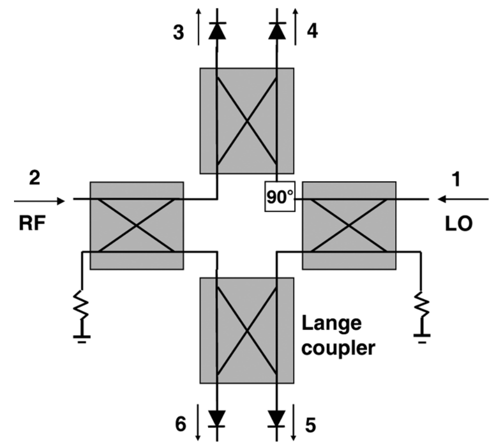

Fig. 1. Block diagram of the six-port network.

This letter proposes an efficient calibration method for the range finder. The calibration is not only for a six-port network, but for a complete radar sensor using the six-port network. Calibration parameters including the phase errors in the passive components as well as the diode characteristics are obtained with the proposed calibration process. The six-port network shown in Fig. 1, comprised of four Lange couplers and four radio frequency (RF) power detectors, was implemented using an InGaP heterojunction bipolar transistor (HBT) process. The size of the radar sensor designed to operate at 24 GHz is 4 cm$\times$ 4 cm.

II. Calibration Equation of the Rangefinder With the Six-Port Network

A passive six-port network can be implemented with four directional couplers and one 90° delay line. There must be an exact 90° phase difference between the outputs in each coupler. However, in reality, the phase difference is not exactly 90° due to process variations. The proposed calibration assumes three phase errors of ϕ_1, ϕ_2 and ϕ_3 in a six-port network as shown in Fig. 2. ϕ_1 and ϕ_2 are associated with the directional couplers connected to input and output ports and ϕ_3 is related to the delayed line. Power detectors convert RF signals into dc voltages in four output ports. Due to the mismatches of the power detectors, the square law in each power detector can be expressed as in [6]

$$V_i = K_i \cdot P_i (i = 3, 4, 5, 6) \tag{2}$$

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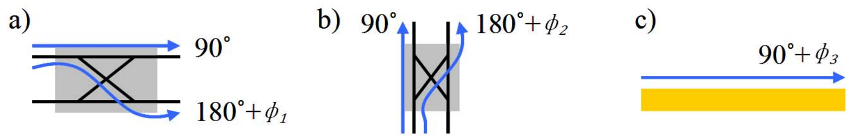

Fig. 2. Phase errors in the six-port network: (a) phase errors in directional couplers connected to input ports, (b) phase errors in directional couplers connected to output ports, and (c) phase error in a 90° delay line.

TABLE I
RELATIVE PHASE RELATIONSHIP BETWEEN THE INPUT AND OUTPUT SIGNALS

	a_1 (reference signal)	a_2 (unknown signal)
b_3 (in port 3)	360° + ϕ_2+ ϕ_3	180 °
b_4 (in port 4)	270° + ϕ_3	270° + ϕ_2
b_5 (in port 5)	270° + ϕ_1	360° + ϕ_1+ ϕ_2
b_6 (in port 6)	360° + ϕ_1+ ϕ_2	270° + ϕ_1

where V_i is the dc voltage, P_i is the RF output power, and K_i is the parameter including the amplitude errors in a six-port network and diode mismatches for each port. Because the received signal is below −20 dB at the range detection of 0.5 m or more, (2) is feasible [6]. There is the assumption, therefore, that seven error elements exist in a six-port network.

When the input signal for each port is expressed as "a_i" and the output signal for each port is expressed as "b_i," the waves at four output ports can be written as a linear combination of the incident signals a_1 (local oscillation (LO) in Fig. 1, a reference signal) and a_2 (RF in Fig. 1, an unknown signal, $a_2 = \alpha \cdot a_1 \cdot \exp(j\Delta\theta)$ where α is the power ratio of the incident signals, and $\Delta\theta$ is the phase difference the reference and the unknown signals). The phase relationship between the input and the output is shown in Table I. The output signals in each port can be expressed as

$$\begin{aligned} b_3 &= 0.5 \cdot a_1 \cdot [\exp[j(\phi_2 + \phi_3)] - \alpha \cdot \exp(j\Delta\theta)] \\ b_4 &= j0.5 \cdot a_1 \cdot [\exp(j\phi_3) + \alpha \cdot \exp[j(\Delta\theta + \phi_2)]] \\ b_5 &= 0.5 \cdot a_1 \cdot [j \cdot \exp(j\phi_1) + \alpha \cdot \exp[j(\Delta\theta + \phi_1 + \phi_2)]] \\ b_6 &= 0.5 \cdot a_1 \cdot [\exp[j(\phi_1 + \phi_2)] + j \cdot \alpha \cdot \exp[j(\Delta\theta + \phi_1)]]. \end{aligned} \tag{3}$$

Using (2), dc output voltages can be expressed as

$$\begin{aligned} V_3 &= K_3' \left[1 + \alpha'^2 - 2\alpha' \cdot \cos(\Delta\theta - \phi_2 - \phi_3)\right] \\ V_4 &= K_4' \left[1 + \alpha'^2 + 2\alpha' \cdot \cos(\Delta\theta + \phi_2 - \phi_3)\right] \\ V_5 &= K_5' \left[1 + \alpha'^2 + 2\alpha' \cdot \sin(\Delta\theta + \phi_2)\right] \\ V_6 &= K_6' \left[1 + \alpha'^2 - 2\alpha' \cdot \sin(\Delta\theta - \phi_2)\right] \end{aligned} \tag{4}$$

where α' is the power ratio of the LO and RF signals considering the phase difference between the RF and LO signal paths in the RF front-end, and K_i' is similar to K_i. Using (4), the phase difference can be expressed as

$$\Delta\theta = \cot^{-1}\left(\frac{\frac{V_4}{K_{43}} - V_3}{\frac{V_5}{K_{53}} - \frac{V_6}{K_{63}}} \cdot \frac{1}{\cos\phi_3} - \tan\phi_3\right) \tag{5}$$

where

$$\begin{aligned} K_{43} &= \left.\frac{V_4}{V_3}\right|_f \cdot \left(\frac{1 + \alpha'^2 - 2\alpha' \cdot \cos(\Delta\theta - \phi_2 - \phi_3)}{1 + \alpha'^2 + 2\alpha' \cdot \cos(\Delta\theta + \phi_2 - \phi_3)}\right) \\ K_{53} &= \left.\frac{V_5}{V_3}\right|_f \cdot \left(\frac{1 + \alpha'^2 - 2\alpha' \cdot \cos(\Delta\theta - \phi_2 - \phi_3)}{1 + \alpha'^2 + 2\alpha' \cdot \sin(\Delta\theta + \phi_2)}\right) \\ K_{63} &= \left.\frac{V_6}{V_3}\right|_f \cdot \left(\frac{1 + \alpha'^2 - 2\alpha' \cdot \cos(\Delta\theta - \phi_2 - \phi_3)}{1 + \alpha'^2 - 2\alpha' \cdot \sin(\Delta\theta - \phi_2)}\right). \end{aligned}$$

To reduce the K_i' parameters in (4), the dc voltages are divided by V_3 in (4). As shown in (5), the phase error term ϕ_1 does not affect the phase difference, as it is assumed that the phase errors in the directional couplers connected to the input ports are identical. In effect, the difference in the phase errors between the couplers is small enough for this assumption to be highly feasible. Equation (5) includes not only the diode characteristics, but also the phase errors of the six-port network. As compared to [5], the expressions in (5) include the phase errors of the passive components and the diode characteristics. Therefore, the calibration with high accuracy can be performed for a range finder using the proposed equations.

III. CALIBRATION PROCESS

A radar sensor using the six-port network measures the distance from the dc output voltages. However, there are numerous sources for dc offset voltages in an actual environment, thus data without the cancellation of the dc offset cannot be used to determine the distance. Under this consideration, a new process for the discovery of the parameters used in the calibration method is proposed.

A reference distance and a starting sweep frequency are determined. The dc offset voltages in all ports are obtained using the averaged data with the RF phases of 0° to 360°, which are generated from the frequency sweep. And the K_{i3} related to the diode characteristics and the phase error ϕ_3 are calculated with the data measured at several frequencies, with the minimum of four frequencies. When the output frequency is changed in a signal generator, the RF phase to the fixed target can be changed at the same distance. If the frequencies are selected for the RF phase to be 0°, 45°, 90°, 135°, the calibration parameters can be expressed as

$$K_{43} = \frac{\frac{V_4'}{V_5' - V_6' \cdot \frac{V_5^\circ}{V_6^\circ}} + \frac{V_4'''}{V_5''' - V_6''' \cdot \frac{V_5^\circ}{V_6^\circ}} - \frac{2V_4''}{V_5'' - V_6'' \cdot \frac{V_5^\circ}{V_6^\circ}}}{\frac{V_3'}{V_5' - V_6' \cdot \frac{V_5^\circ}{V_6^\circ}} + \frac{V_3'''}{V_5''' - V_6''' \cdot \frac{V_5^\circ}{V_6^\circ}} - \frac{2V_3''}{V_5'' - V_6'' \cdot \frac{V_5^\circ}{V_6^\circ}}} \tag{6}$$

$$K_{53} = \frac{\frac{V_4''}{K_{43}} - V_3''}{\sin\phi_3 \cdot \left(V_5'' - V_6'' \cdot \frac{V_5^\circ}{V_6^\circ}\right)} \tag{7}$$

$$K_{63} = K_{53} \cdot \frac{V_6^\circ}{V_5^\circ} \tag{8}$$

TABLE II
CALIBRATION CONDITIONS AND PARAMETERS

Reference Distance	1.5 m
Averaging for DC offset	5 times
Selected RF phases [a]	0°, 45°, 90°, 135°
K_{43}	1.484
K_{53}	1.595
K_{63}	3.046
ϕ_3	0.751°

[a] Selected RF phases are generated by controlling the output frequencies with a target position fixed.

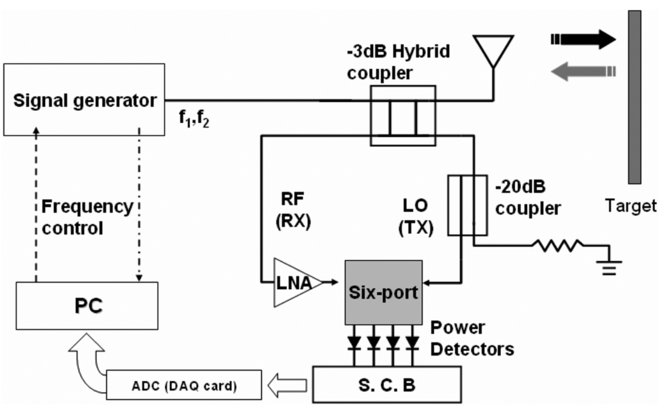

Fig. 3. Block diagram of a radar sensor using a six-port network.

$$\sin\varphi_3 = \pm\sqrt{\frac{\frac{V_4''}{K_{43}} - V_3''}{2\left(V_5'' - V_6'' \cdot \frac{V_5^\circ}{V_6^\circ}\right)} \cdot \left(\frac{\frac{V_4'}{K_{43}} - V_3'}{V_5' - V_6' \cdot \frac{V_5^\circ}{V_6^\circ}} + \frac{\frac{V_4'''}{K_{43}} - V_3'''}{V_5''' - V_6''' \cdot \frac{V_5^\circ}{V_6^\circ}}\right)} \quad (9)$$

where $V_i|_{\mathrm{at}0^\circ} = V_i^\circ$, $V_i|_{\mathrm{at}45^\circ} = V_i'$, $V_i|_{\mathrm{at}90^\circ} = V_i''$, $V_i|_{\mathrm{at}135^\circ} = V_i'''(i = 3,4,5,6)$

The calculated calibration parameters in Table II are assumed to be constant in the frequency bandwidth of 112.5 MHz ($0^\circ \sim 135^\circ$) because the difference of these parameters is small enough to be acceptable. The calibration parameters including the effect of the phase errors can be obtained from dc output voltages measured by varying the output frequency. Therefore, the complete range finder with the six-port network is simply calibrated using the proposed equations.

IV. Measurement Results

The distance to the target can be detected from the phase difference between a transmitted signal and a received signal. Using two adequately spaced CW frequencies, here f_1 and f_2, the distance can be expressed as in [3]

$$d = \frac{c \cdot \Delta\theta_f}{4\pi(f_1 - f_2)} \quad (10)$$

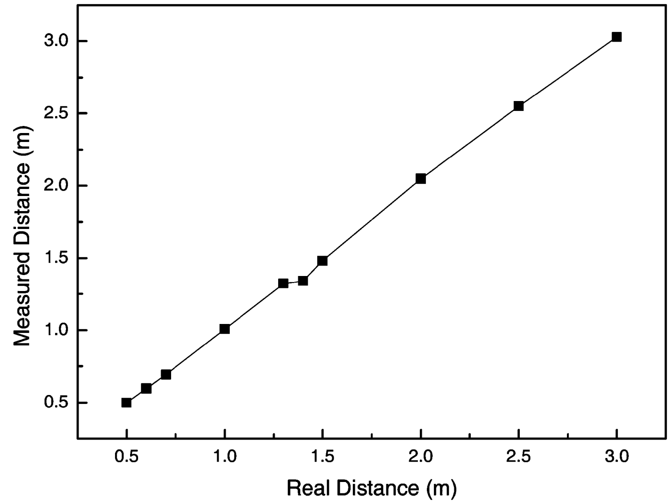

Fig. 4. Measured distances with two frequencies using the calibration parameters in Table II. (Range accuracy; ∼2% error.)

where c is the velocity of light and $\Delta\theta_f$ denotes the difference of the phase difference between the LO and RF signals$\Delta\theta_f = \Delta\theta_{f_1} - \Delta\theta_{f_2}$.

The radar sensor for range detection consists of a six-port discriminator, a LNA, a signal conditioning block, an antenna, a signal generator, a PC, and a DAQ unit, as shown in Fig. 3.

Fig. 4 shows the measured distance using the calibration parameters from Table II. The maximum range is limited by the Tx leakage signal. The dc offset voltages are canceled before the range detection. The maximum distance error is approximately 2%.

V. Conclusion

An efficient calibration of a radar sensor with a six-port network is proposed. The effects on the phase errors in the six-port network are considered. This is an accurate method for a range finder that utilizes a six-port network. The calibration parameters are simply obtained using the proposed process. A range finder with the method is demonstrated via distance measurements from 0.5 to 3 m, with a maximum error of 2%.

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