A Displacement Measurement Technique Using Millimeter-Wave Interferometry

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***Abstract*—A displacement measurement sensor, capable of sub-millimeter resolution, using millimeter-wave interferometry has been developed. The sensor operates at 37.6 GHz and is realized using both microwave integrated circuits and monolithic microwave integrated circuits. It has been used to accurately measure the displacement of metal plate location and water level. A resolution of only 0.05 mm is achieved. A maximum error of 0.3 mm is also attained without correction for the nonlinearity of the phase-detection processor and agrees well with the theoretical calculation.**

***Index Terms*—Displacement measurement, microwave interferometer, millimeter-wave interferometer, sensor.**

I. Introduction

MICROWAVE interferometry has been widely used for various applications in instrumentation such as nondestructive characterization of material [1] and plasma diagnostics [2]. Interferometery is an ideal means for displacement measurement due to its high measurement accuracy and fast operation. It particularly has high resolution due to the fact that the displacement is resolved within a fraction of a wavelength of the operating frequency. Previous works based on optical interferometers have been reported for displacement measurements with resolution ranging from micrometer to sub-nanometer [3]–[5]. Fast and accurate displacement measurement is needed in various engineering applications such as high-speed metrology, position sensing, and liquid-level gauging.

In this paper, we report on the development of a new displacement-measurement interferometric sensor with sub-millimeter resolution. The system operates at 37.6 GHz and is completely fabricated using microwave and millimeter-wave integrated circuits—both hybrid [microwave integrated circuit (MIC)] and monolithic [monolithic microwave integrated circuit (MMIC)]. Measured results show a resolution of only 0.05 mm and error of 0.3 mm (without correction for the quadrature-mixer's phase nonlinearity).

II. System Principle

Fig. 1 shows the overall system block diagram. The sensor transmits a millimeter-wave signal to illuminate a target via the antenna. The return signal from the target is captured by the sensor via the antenna and converted into a baseband signal, which is then processed to determine the displacement of the target location.

Displacement measurement using the interferometry technique is basically a coherent phase-detection process using a phase-detecting processor, which is quadrature mixer in our system. The phase difference between the reference and measurement paths, produced by a displacement of the target location, is determined from the in-phase (I) and quadrature (Q) output signals of the quadrature mixer. These signals are described as

$$\begin{aligned} v_I(t) &= A_I \sin\phi(t) \\ v_Q(t) &= A_Q \cos\phi(t) \end{aligned} \tag{1}$$

where A_I and A_Q are the maximum amplitudes of I and Q signals, respectively. $\phi(t)$ represents the phase difference and can be determined, for an ideal quadrature mixer, as

$$\phi(t) = \tan^{-1}\left(\frac{v_I(t)}{v_Q(t)}\frac{A_Q}{A_I}\right). \tag{2}$$

Practical quadrature mixers, however, have a nonlinear phase response due to their phase and amplitude imbalances, as well as dc offset. A more realistic form of the phase can be expressed as

$$\phi(t) = \tan^{-1}\left(\frac{1}{\cos\Delta\phi}\frac{A_Q}{(A_I+\Delta A)}\frac{v_I(t)-V_{\text{OSI}}}{v_Q(t)-V_{\text{OSQ}}} - \tan\Delta\phi\right) \tag{3}$$

where V_{OSI} and V_{OSQ} are the dc offsets of the I and Q signals, respectively. ΔA and $\Delta\phi$ represent the amplitude and phase imbalance between the I and Q channels, respectively.

The range from the antenna to the target relates to the detected phase and the incidence angle of the beam as

$$r(t) = \frac{\phi(t)}{4\pi\cos\theta_i}\lambda_0 \tag{4}$$

where λ_0 is the operating wavelength in air and θ_i is the beam's incidence angle. Note that the detected phase corresponds to a round-trip travel of the received signal.

Range variation is produced by changes in target location and can be expressed in the time domain as

$$\Delta r(nT) = r[nT] - r[(n-1)T] \qquad n = 1, 2, 3, \ldots \tag{5}$$

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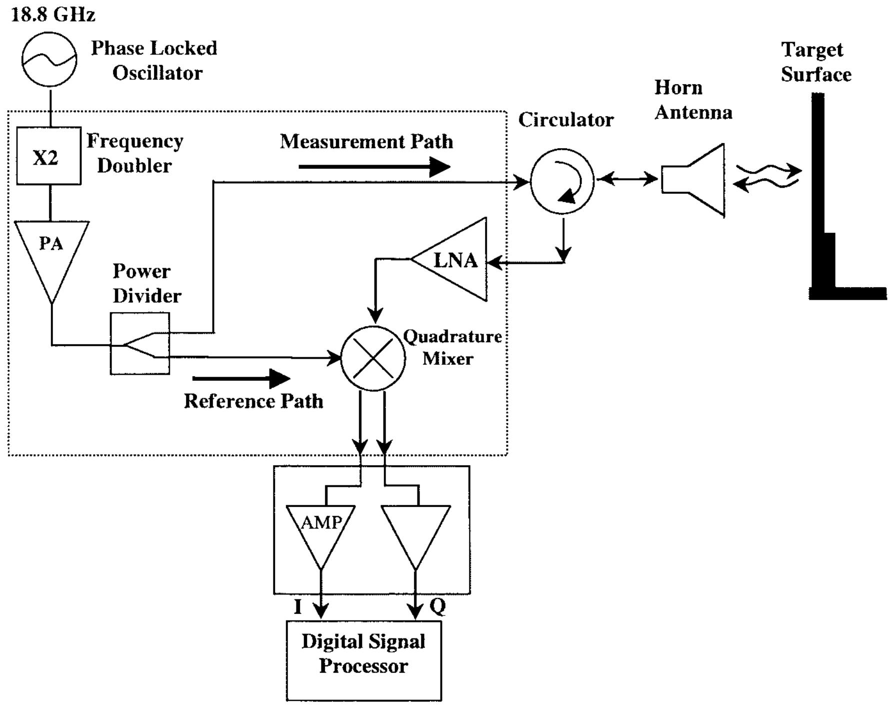


Fig. 1. Overall system configuration.

where T is the sampling interval. The displacement for the entire target measurement sequence can be described as a summation of consecutive range variations

$$d(nT) = \sum_{n=1}^{k} \Delta r(nT) \qquad n = 1, 2, 3, \ldots, k. \tag{6}$$

These range variations can be measured from the data acquisition and processing of the quadrature mixer's output signals, from which an actual displacement can then be constructed. In this displacement construction process, the range ambiguity problem arises due to the 2π-phase discontinuity of the phase-detecting processor, which is typically expected in the interferometry technique. This problem is overcome by employing the phase unwrapping signal-processing technique described in [6]–[8]. Measured data produced by the interferometer are wrapped into the range $(-\pi, \pi]$, and the phase unwrapping algorithm is used to reconstruct the wrapped phase beyond the range of $(-\pi, \pi]$ so as to obtain a continuous phase without the 2π radian ambiguities.

III. Fabrication and Test

The millimeter-wave interferometric sensor has been fabricated using MICs and MMICs. All components inside the dotted lines shown in Fig. 1 are integrated on a 0.25-mm alumina substrate using surface-mount technology. The Wilkinson power divider directs the millimeter-wave signal into the reference and measurement paths. Commercially available Ka-band MMICs were used for the quadrature mixer (AM038R1-00, Alpha Industries, Woburn, MA), low-noise amplifier (ALH208C, TRW, El Segundo, CA), power amplifier (TGA1071-EPU, TriQuint, Dallas, TX), and frequency doubler (TGC1430F-EPU, TriQuint, Dallas, TX); they are surface mounted on metallic patches connected to the alumina's ground plane by 0.2-mm-diameter vias. Printed circuit board (PCB) is used to mount a high-precision operational amplifier, which constitutes a 100-Hz passband active low-pass filter. The filter provides gain for the output signals of the quadrature mixer and limits the signal bandwidth to reduce the noise-floor level. 76.2 $\times$ 12.7 μm gold ribbons are used to connect the 0.25-mm-wide alumina transmission lines to the signal pads on the MMICs. Fig. 2 shows a photograph of the fabricated system.

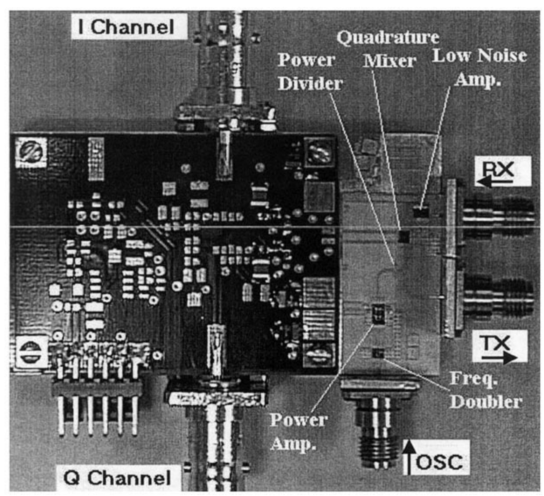
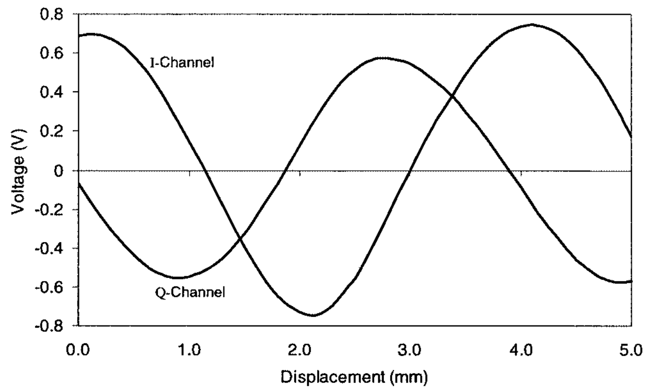
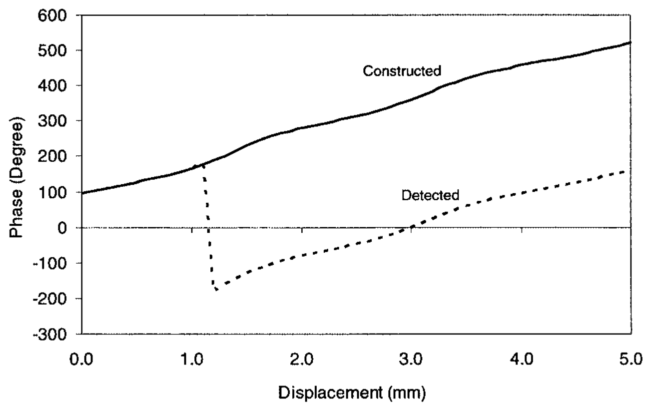


Fig. 2. Photograph of the fabricated system.

We tested the sensor using two laboratory samples. An 18.8-GHz phase-locked source and a Ka-band standard horn antenna were used in the tests. The first sample is a metal plate mounted on an XYZ-axis stage. The XYZ-axis stage has a fine variation precision of 0.01 mm, a high accuracy of 0.002032 mm/25.4 mm, and a good repeatability of



(a)



(b)

Fig. 3. (a) Measured signal voltage. (b) Detected and constructed phase.

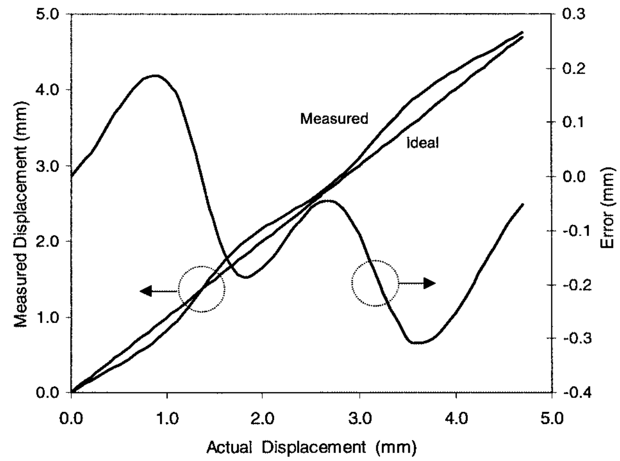
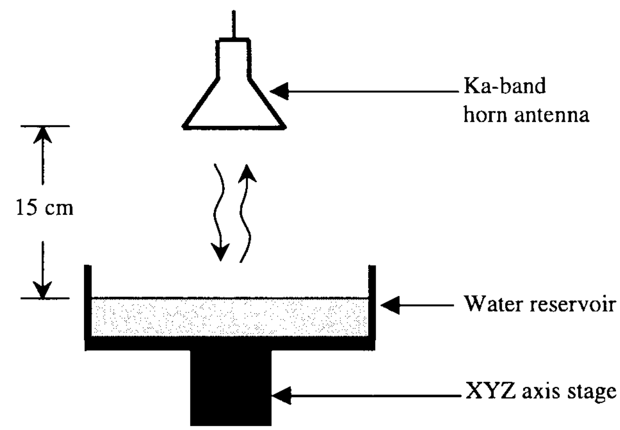
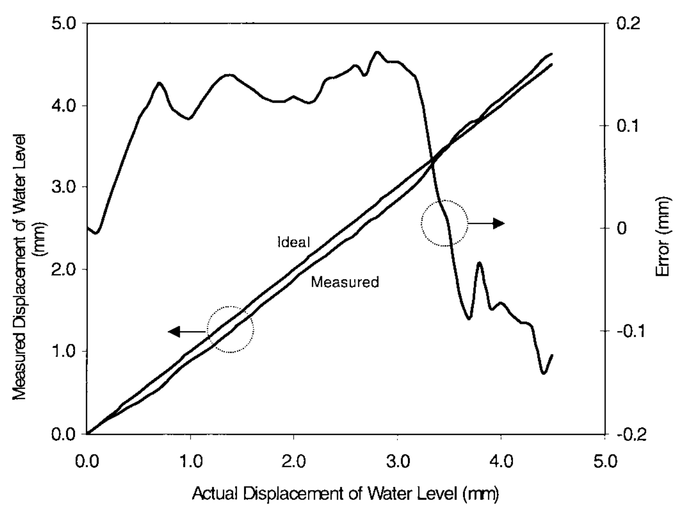


Fig. 4. Measured displacement for a metal plate.



(a)



(b)

Fig. 5. Measurement setup for: (a) water level gauging and (b) test results.

0.00127 mm. The metal plate was located 30 cm away from the antenna aperture, and the displacement measurement was made as the plate was moved every 0.1 mm. Signals from the quadrature mixer were captured by the data acquisition hardware and averaged to cancel out the noise components in the signal processing. Fig. 3(a) shows the measured signal voltages, excluding dc-offset voltage, needed for the phase unwrapping. Fig. 3(b) displays the phase detected and constructed by the phase unwrapping technique. The phase detected was determined from

$$\phi(t) = \tan^{-1}\left(\frac{v_I(t) - V_{\rm OSI}}{v_Q(t) - V_{\rm OSQ}}\right) \tag{7}$$

which contains the errors resulting from the amplitude and phase imbalances of the quadrature mixer. As can be seen in Fig. 3(b), the reconstructed phase varies from 95° to 523° for a displacement of 5 mm. This range of phase variation is sufficient to validate the phase unwrapping signal processing for phase reconstruction without the 360° ambiguities. For displacements corresponding to multiple times of 360°, an iterative process of the phase unwrapping is needed to construct the phase. The final displacement result is shown in Fig. 4 together with the measurement error.

The second sample, as shown in Fig. 5(a), is water stored in a reservoir, which is mounted on an XYZ-axis stage. It is used to demonstrate a possible application of liquid level gauging. The water level was located at a distance of 15 cm from the horn antenna and the measurement was made as the distance was varied. Fig. 5(b) shows the measured displacement and corresponding error.

In both measurements, the sensor achieves a measured resolution of only 0.05 mm and a maximum error of 0.3 mm at each displacement. The resolution was determined through the measurement of the minimum detectable voltage (or phase) as the displacement was changed. The error is mostly attributed to the

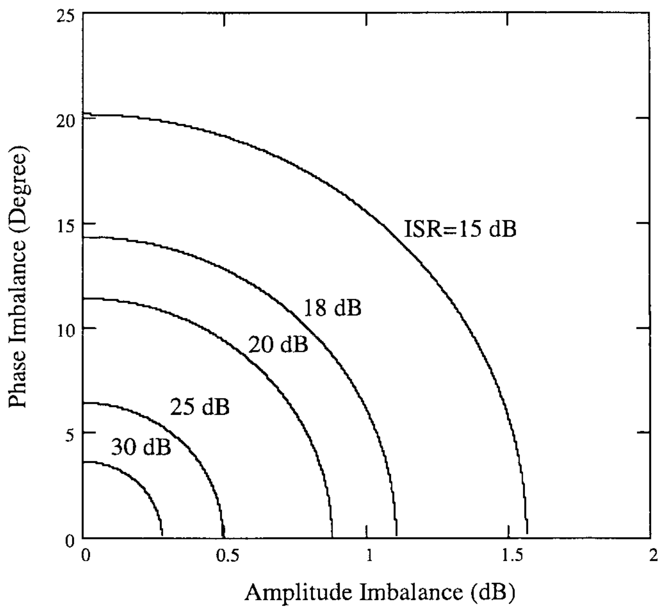


Fig. 6. Constant ISR contours.

nonlinear response of the quadrature mixer. Several techniques have been proposed to correct the nonlinearity of the quadrature mixer [9], [10]. Possible sources of error also come from the measurement distance, the target's reflecting surface, or a combination of these. The instability of the frequency source should produce negligible effect on the measurement due to the short time delay between the transmit and receive signals of the sensor. The sensor can also operate at larger ranges (e.g., 3 m) with proper transmitting power.

Measurement accuracy was estimated by an analysis of the maximum phase imbalance using the method proposed in [11]. In this method, the maximum phase error resulting from the image rejection level of the quadrature is calculated. The image-to-signal ratio (ISR) as a function of the amplitude and phase imbalance can be approximately derived as

$$\mathrm{ISR} = \frac{1 + V_e^2 - 2V_e \cos\phi_e}{1 + V_e^2 + 2V_e \cos\phi_e} \tag{8}$$

where V_e and ϕ_e are amplitude and phase imbalance, respectively. Equation (14) can be approximated by an ellipse

$$\left(\frac{\phi_e}{X}\right)^2 + \left(\frac{V_e}{Y}\right)^2 = 1 \tag{9}$$

where

$$X = \cos^{-1}\left(\frac{1 - \mathrm{ISR}}{1 + \mathrm{ISR}}\right)$$
$$Y = \frac{1 + \sqrt{\mathrm{ISR}}}{1 - \sqrt{\mathrm{ISR}}}.$$

Fig. 6 shows constant ISR contours for several different ISR values of a quadrature mixer. As can be seen, the maximum phase imbalance occurs when the amplitude imbalance is 0 dB. Using an ISR of 18 dB from the employed quadrature mixer's data sheet [12], we obtain a maximum phase error of 14.4°, which corresponds to a maximum distance accuracy of 0.32 mm. The measured error of 0.3 mm shown in Figs. 4 and 5(b) falls within the maximum calculated error.

IV. Conclusion

A new millimeter-wave interferometric sensor has been developed and demonstrated for accurate displacement sensing and liquid level gauging. From the experimental results, it has been found that sub-millimeter resolution in the order of 0.05 mm is feasible. A measurement accuracy of 0.3 mm was also measured and is within the maximum error calculated by the worst-case error analysis. The measured results demonstrate the workability of the developed sensor and its potential as an effective tool for displacement measurement and liquid level gauging.

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