A New Millimeter-Wave Step-Frequency Radar Sensor for Distance Measurement

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***Abstract*—A new compact millimeter-wave distance-measurement sensor prototype has been developed. The sensor is a step-frequency radar implemented using coherent heterodyne technique. It operates in Ka-band (26.5–40 GHz) and is realized using MICs and MMICs. The sensor transmits sinusoidal signals of incremental frequencies and demodulates the received signals into base-band I/Q signals for processing. Experimental results show that the sensor is capable of measuring distance with less than 0.2 inch of absolute error and a low transmitted power of only -20 ± 3 dBm.**

***Index Terms*—MIC, microwave sensor, MMIC, sensing of distance.**

I. Introduction

MICROWAVE sensors have been used for accurate, non-contact measurements of distance in various applications—for example, level measurements in chemical storage tanks. Most microwave distance-measurement sensors operate below 24 GHz, particularly at 5.8 and 10 GHz. Millimeter-wave sensors offer smaller size, lighter weight, finer resolution, better accuracy, and are thus attractive for industrial applications. Recently, a millimeter-wave sensor has been developed at 35 GHz using a six-port receiver for distance measurement [1].

In this paper, we report a new millimeter-wave sensor prototype operating in Ka-band (26.5–40 GHz) for distance measurement. The sensor is based on step-frequency radar implemented using a coherent heterodyne scheme. It is realized using microwave and millimeter-wave integrated circuits—both MICs and MMICs. It operates at a very low power level—around -20 dBm—and can accurately measure target distance.

II. Principle of Step-Frequency Radar

Step-frequency radar (SFR) was first proposed in 1972 as a time-domain reflectometer [2]. Basically, SFR operates as a frequency-modulation system—transmitting sequences of sinusoidal signals of different frequencies toward a target and processing the return signals. In each sequence, the frequency is shifted in discrete values—each value is held constant for a period of time and then changed to a next higher value. The received signals at these step frequencies, reflected from the target, are down-converted into in-phase (I) and quadrature-phase (Q) signals in base band. These I and Q signals are sampled and combined to form an array of complex signals—each corresponding to a step frequency—which are transformed using inverse Fourier transform. The resultant waveform, compressed in time relative to the duration of the transmitted signal, is then processed to reveal the distance to target. The SFR sensing technique allows target distance to be measured with large range, high accuracy, and small measurement ambiguity.

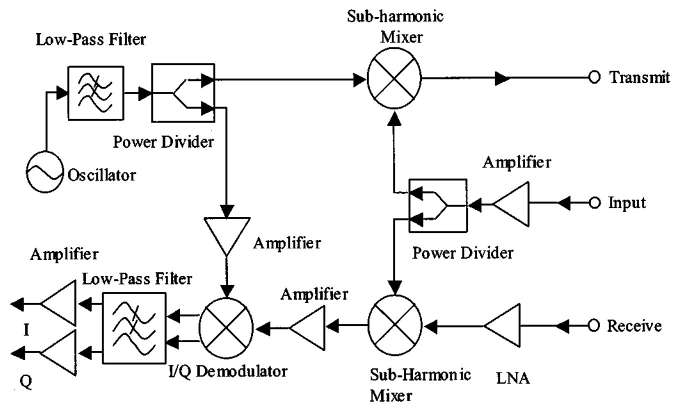

Fig. 1. System configuration of the millimeter-wave SFR sensor.

III. Sensor Design and Performance

Fig. 1 shows the configuration of the developed millimeter-wave sensor. This sensor employs SFR along with a coherent heterodyne architecture. The sensor is fabricated using a hybrid approach consisting of both MICs and MMICs. The MICs are on 50-mil RT/Duroid 6010 substrate (for low-frequency circuits) and 10-mil alumina substrate (for high-frequency circuits). The size of the sensor is 4-in $\times$ 6-in.

The oscillator generates a signal of 1.7 GHz, which is used as the LO signal for the I/Q demodulator and the IF signal for one of the subharmonic mixers. This subharmonic mixer up-converts the incoming 14–15.59 GHz signals from an external synthesizer to 29.7–32.88 GHz signals, which are transmitted toward a target. The return signals from the target are down-converted by the other subharmonic mixer, which are then further converted into base-band I and Q signals by the I/Q demodulator. The I/Q signals are sampled by an analog-to-digital converter and combined to form an array of complex signals, which are transformed into a time-compressed waveform using an inverse Fourier transform algorithm. This signal is then processed by LabView software [3] to determine the target distance.

Fig. 2 shows the system test setup for measuring target distance. The target is a 4-in. $\times$ 4-in. metal plate or ceramic

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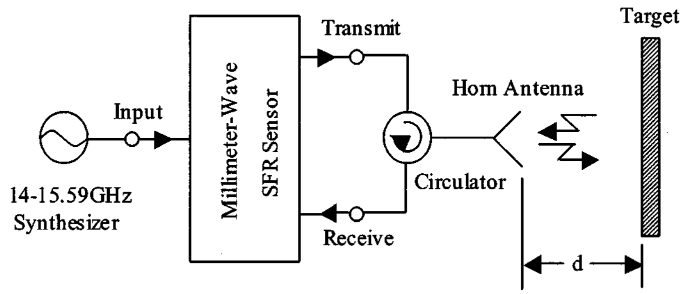

Fig. 2. Test setup for distance measurement.

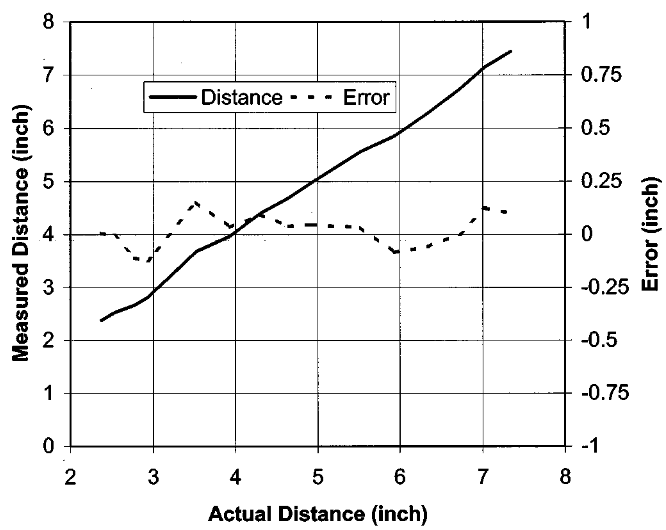

Fig. 3. Comparisons between the measured and actual distances from the sensor to a metal plate.

tile. The antenna, a Ka-band horn of 20-dB gain, was pointed directly onto the target, without contact, through air. The sensor transmitted only -20 ± 3 dBm over the entire operating frequency range. In the measurements, 160 frequency steps with increments of 10 MHz, were used. Consequently, 160 pairs of base-band I/Q signals were sampled from the signals returned from the target, and used to form 160 complex signals. In order to apply a fast Fourier transform (FFT) algorithm and smooth the transformed signal, we added additional 864 zeroes to the complex-signal array. These discrete 1024 samples, windowed by a rectangular window function, were then transformed into a time-compressed waveform by inverse FFT. Finally, a bin number signifying the target position corresponding to the location of the peak in the transformed waveform, identified by a simple search, was converted into a distance value. Figs. 3 and 4 show the measured and actual distances from the antenna to the metal and tile targets along with the errors, respectively. The measurement error is mainly caused by the system's range resolution, which is calculated as 0.19 inch for the transmitted signal's bandwidth of 3.2 GHz in air. Several measurements

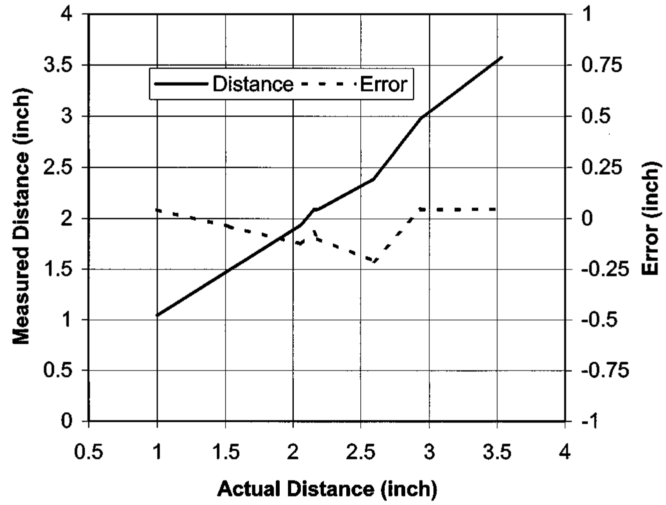

Fig. 4. Comparisons between the measured and actual distances from the sensor to a ceramic tile.

were made at each distance and the results were averaged. As can be seen, the sensor produces a good accuracy with errors of less than 0.2 inch, for both the metal plate and ceramic tile. Note that this is an absolute error regardless of the distance. The measurement accuracy of the system is not affected by a direct transmitter leakage into the receiver and multiple reflections due to their different arrival times with respect to the received signal returned from target.

IV. Conclusion

A new millimeter-wave distance-measurement sensor prototype—based on the step-frequency radar and coherent heterodyne technique—has been developed in Ka-band using MICs and MMICs for the first time. The sensor operates at a very low power level of -20 ± 3 dBm. Distance measurements have been made to verify the performance of this sensor prototype, and small errors between the measured and actual distances have been achieved.

Acknowledgment

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