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Range Measurement Using Modulated Retro-Reflectors in FM Radar System

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***Abstract*—In a variant of the FM radar technique, an essentially clutter-free range measurement may be made to a cooperative target. To enhance the link budget in such a measurement system, modulated retro-reflectors are demonstrated as passive transponders which maintain a high radar cross section over a wide range of RF incidence angles. Range measurement accuracies the order of 1 cm are demonstrated in a high-clutter indoor environment.**

I. Introduction

WHILE many approaches to radar clutter rejection assume little prior knowledge of the spectrum of the wanted target, here, we demonstrate a scheme whereby the target's radar signature is known and coded to maximize its visibility to a particular illuminating signal. Such a transponder may be used as a beacon, e.g., at the entrance to a harbor, or at an aircraft landing site. Since the transponder is not an RF transmitter, it has advantages in applications requiring covert communications or minimal power consumption. In contrast to systems employing a single-element scatterer [1] the range of operation is greatly enhanced by the increased radar cross section of the retro-reflecting aperture. This ensures enhanced gain over a wide range of look angles [2], [4], compared to a single element scatterer. Whilst a wide range of communications applications are possible, we here present an FM ranging system.

II. X-Band Transponder Prototype

Retro-reflector transponders realized as printed circuits operating at 2.5 GHz have been reported by the authors [3]. Similar techniques were used to construct transponders operating at 9.2±0.2 GHz, thus covering an important maritime band. A 4×4 array of linearly polarized, aperture coupled patch antennas was again used. The antenna matrix was photo-etched onto *Taconic TLC* microwave laminate ($\varepsilon_r = 3.0$, $h = 0.79$ mm) which yielded the required 10 dB bandwidth of 300 MHz centered at 9.2 GHz. The antenna dimensions were 8.8 mm^2, while their spacing was 22 mm. The microstrip feed lines, which inter-connect antenna pairs, incorporated the phase switches which perform the modulation of the reflected signal. Each switch utilized four silicon beam lead PIN diodes bonded to the microstrip lines using silver epoxy. The circuits measured 100 mm^2—their layouts are shown in Fig. 4.

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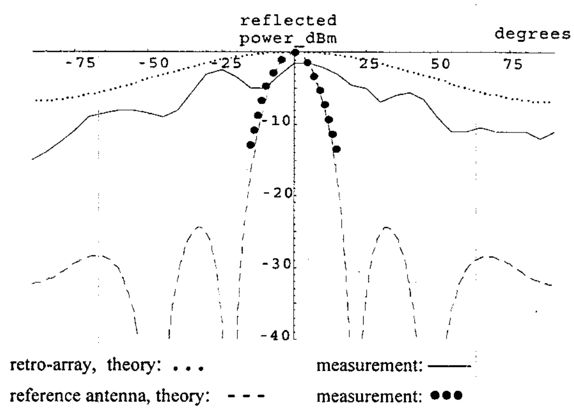
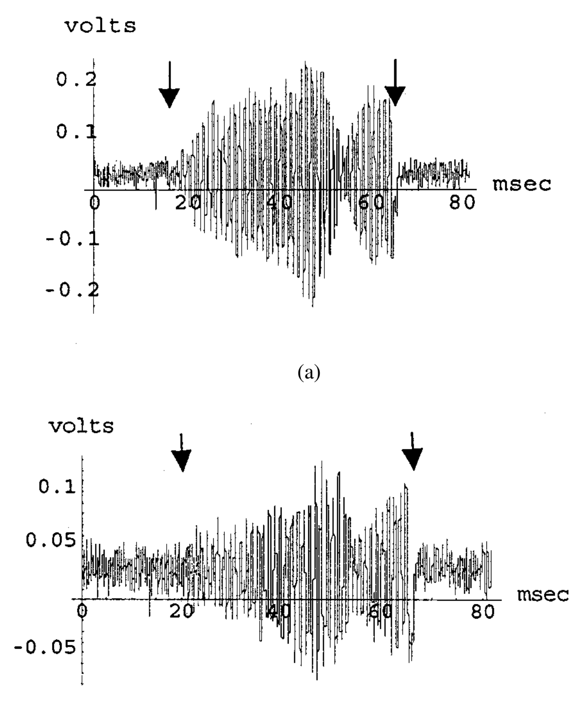


Fig. 1. RCS calibration results ! reflected power in first sideband.



(b)

Fig. 2. Typical time domain waveforms for FM range measurement. Range = 1589 cm ±0.6 cm (a) Transponder on boresight. (b) Transponder at 75° (E-plane rotation).

To estimate the efficiency of the retro-reflector a conventional 16 element printed array antenna was fabricated to act as a reference. The reference antenna utilized the same 16 element matrix on the same substrate. The power of the reflected

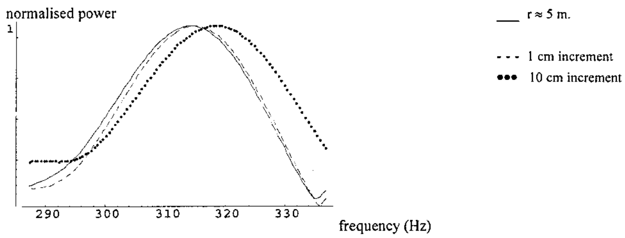


Fig. 3. FM range measurement: FFT peaks following zero padding

modulation products was studied for both structures—the RCS of the reference antenna was phase modulated by connecting in series with a phase shifter to which the modulation signal was applied. Fig. 1 shows the reflected power for the E-plane angular response of both structures at an illuminating RF frequency of 9.2 GHz and a modulation frequency of 1 MHz. While the retro-array shows strong modulation products over 180° of illumination angle the reference antenna maintains an equivalent RCS over only 26°. Efficient modulation was also observed up to rates of 10 MHz. Phase switch power consumption in the retro- array amounted to 70 μW. The peak modulation power (hence RCS) of the retro-array was 1.5 dB lower than the antenna array, the additional loss in the former being attributable to the additional transmission line lengths and the loss in the switching diodes. Since the gain of the reference antenna was 16.5 dBi, the retro-reflector's peak RCS was calculated to be 0.1 m^2.

III. FM Range Measurement

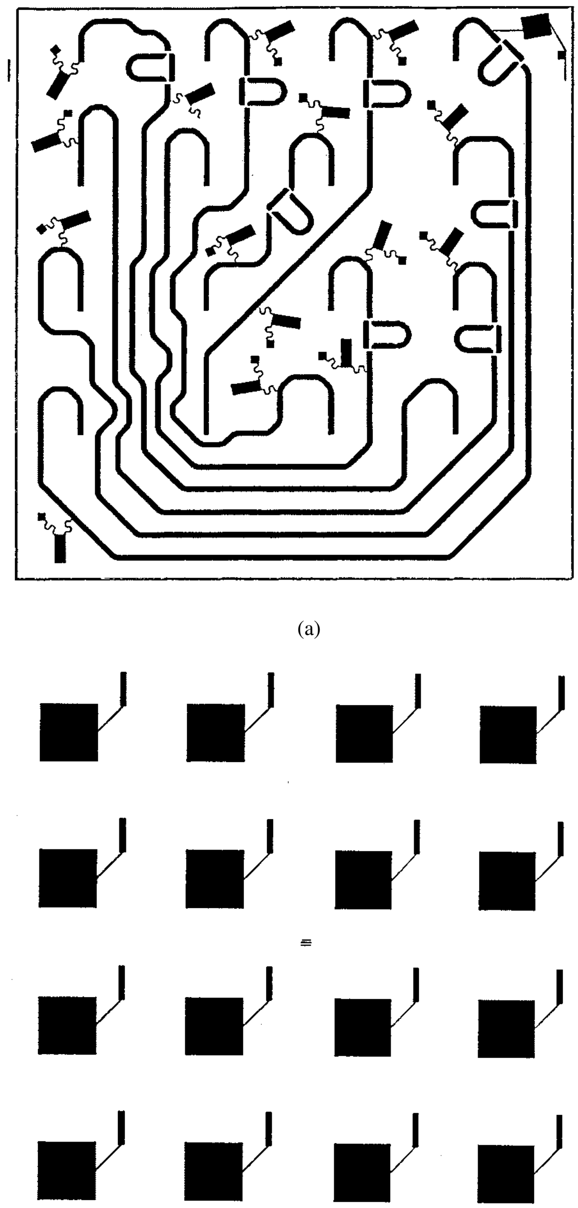
FM range finding to a cooperative scatterer is an established technique [1]. Conventionally, the RF mixer compares the transmitted frequency with the received frequency, the difference Δf being directly proportional to the time interval and hence path length 2 L between the transmitted and received signal, hence

$$\Delta f = \frac{Fstop - Fstart}{Tsweep} \cdot \frac{2L}{c} \tag{1}$$

where F_{start} and F_{stop} are the start and stop frequencies in the linear frequency ramp of duration T_{sweep}, and c is the speed of light. When the RCS of the target is modulated (at f_{mod}) the reflected spectrum contains components at $f_{mod} \pm \Delta f$. Thus Δf may be detected by a simple envelope detector following a bandpass filter centered at f_{mod}. (For convenience, coherent detection was used in the laboratory demonstration.) This process effectively rejects all other, unmodulated targets. The technique lends itself to refinement by using multi-tone modulation or a pseudo random binary sequence.

IV. Results

The modulated retro-reflector described above was illuminated with a horizontally polarized signal sweeping from 9.0 to 9.4 GHz in 50 ms. Fig. 2 shows typical time domain waveforms for difference frequency—the arrows shows the start and



(a)

(b)

Fig. 4. Modulated retro-reflector—layout of printed circuits. (a) Microstrip feed lines and switches. (b) Radiating elements.

stop points of the sweep. The 8 GHz/s rate gives rise to a difference frequency Δf of 53 Hz/m of range. Hence, the basic FFT resolution, given by the reciprocal of the time domain file duration, is 20 Hz for the 50 ms sweep. This approach would therefore yield a measurement accuracy of 0.377 m. To improve upon this accuracy signal processing algorithms were developed which employed padding the time domain file with 48K of zeros followed by FFT and quadratic curve fit to the FFT peak, then maximum search. Range increments of 1 cm could be discriminated by this technique. The FFT's after padding are shown for three cases in Fig. 3, where the range increments were 1 cm and 10 cm.

Calibration: The various path lengths of the RF components add a constant offset (error term) to the measurement. This term was established by comparison with another range sensor ie. a tape measure. Plotting difference frequency against range yields a straight line, whose gradient is a function of the FM ramp

$$\frac{\partial f}{\partial r} = \frac{B}{Tsweep}\frac{2}{c}$$

and whose y-intercept is the constant calibration term. (2)

A linear fit to a number of calibration data yielded a y-intercept of 36.96 Hz. Hence, for the 8 GHz/s sweep

$$r = \frac{\Delta f - 36.96}{0.5333}$$

where Δf is given in hertz and r in centimeters. (3)

While a full statistical analysis is beyond the scope of the Letter, the accuracy of the system beyond a few meters exceeded that of the tape measure. Incremental steps up to 1 m. were measured to an accuracy not worse than 1.7 cm, while increments as low as 1 cm were discriminated by the system. Returning to the time domain data from Fig. 2, difference frequencies of 884.05 Hz and 884.72 Hz were obtained for the on-boresight and 75° cases, respectively, giving ranges 1588.4 cm and 1589.6 cm from (3). Thus, the 75° E-plane rotation gave rise to a 1.2 cm measurement error.

V. CONCLUSIONS

A technique for range measurement using FM illumination of a modulated microwave retro-reflector has been demonstrated. Retro-reflector prototypes have been fabricated from planar circuits comprising an antenna matrix and solid state switches. The link budget is enhanced by the RCS of the array, which is weakly dependent on look angle. Clutter in the measurement is effectively suppressed by detection of the known modulation waveform. Range measurement accuracy is dependent on the measurement of difference frequency in the FM system. Measurement accuracies of 1 cm were demonstrated in the laboratory. In a system employing a rotating high gain antenna, a single transponder will provide range and bearing information. However, if a number of transponders using different modulation codes are employed, positional triangulation may be achieved from a fixed or omnidirectional antenna beam.

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