Low-Power X-Band Radar for Indoor Burglar Alarms

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Abstract—**Design and realization of a hybrid microwave integrated circuit (HMIC) for a low-power X-band Doppler effect radar system is presented. The radar operates within the range 9.9 $\div$ 10.5 GHz. The system is able to detect the frequency shift between the transmitted and the target reflected signal, providing an IF signal output that can be used for different types of post-processing. The design of the different units composing the system is detailed. Application of this system to indoor intrusion alarms is also fully described.**

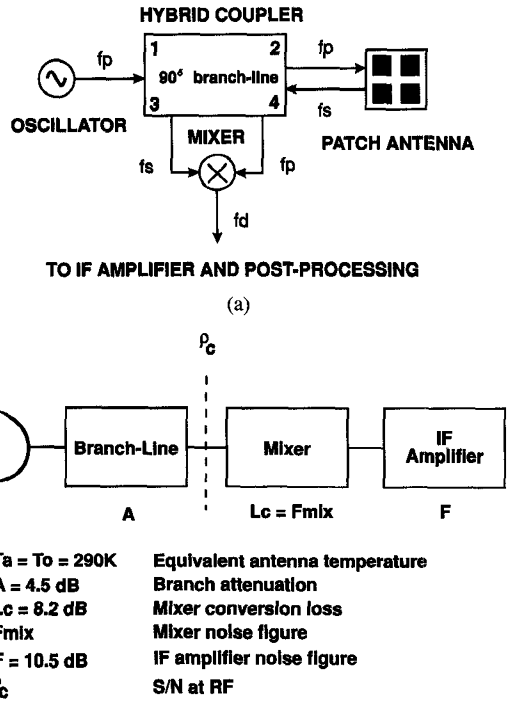
I. Introduction

The purpose of the project has been the development of a suitable radar system for indoor intrusion alarm application, however this system could be also used for speed measurements, environmental monitoring and distance measurements using different IF signal post-processing and eventually modifying the radiating elements according to the peculiarities of the application.

The signal generated by the oscillator (frequency f_p) is splitted by means of a branch-line hybrid coupler, which feeds the transmitting antenna and one of the two ports of the mixer (acting as a local oscillator reference on the receiving path). The other input port of the mixer is fed with the receiving RF signal coming from the antenna (frequency f_s), in order to obtain on the low frequency output a signal which is the difference between the transmitted and the received signals (frequency f_d), (Fig. 1(a)).

The system works within the 9.9 $\div$ 10.5 GHz frequency range, where most of the countries (e.g. France, Germany, Italy, UK., USA) recommendations allocate this kind of applications. It meets and exceeds the constraints on maximum radiated field strength of 25 mV/m, measured at 1 m from the antenna, which corresponds to a radiated power of +25 dBm. The cost is significantly reduced by the use of 0.6 mm epoxy glass substrate (FR4) and plastic packaged devices (SOT-23 and SOT-143), while high reliability and good performance make this realization suitable for commercial and consumer circuits.

The circuit is biased with a single positive voltage ($V_{cc} = 5$ V $\pm$ 0.5 V). The operating temperature is within $-25°$C $\div$ 60°C, and the frequency drift is below 10 MHz with an output power variation less than 1 dB over the whole temperature range. The use of a single 4-patch antenna has been preferred, instead of using two different 2-patch antennas on the transmitting and receiving path, to increase (ideally 3 dB) the total link budget by means of a double antenna gain, using the same radiating area.



(b)

Fig. 1. (a) Block diagram of the system; f_p is the generated frequency, f_d is the Doppler frequency and $f_s = f_p \pm f_d$ is the frequency of the signal received from the antenna. (b) Schematic of the circuit as a receiver.

II. System Design

To obtain a product suitable for the consumer market, the key design features we performed have been directly related to the limitation in terms of cost, reduced size and high repeatability over the frequency range.

The size of the device is limited to 25 cm^2 to match practical applications requirements; this constraint limits the performance of the radiating elements. The maximum gain obtainable from the patch antenna is 12 dB at 10 GHz, thus the maximum power supplied to the antenna must be lower than 13 dBm.

To get a signal to noise ratio S/N = 20 dB, by imposing the minimum power to the antenna $P_T = +5$ dBm, an IF

Manuscript received May 27, 1994; revised January 30, 1995.

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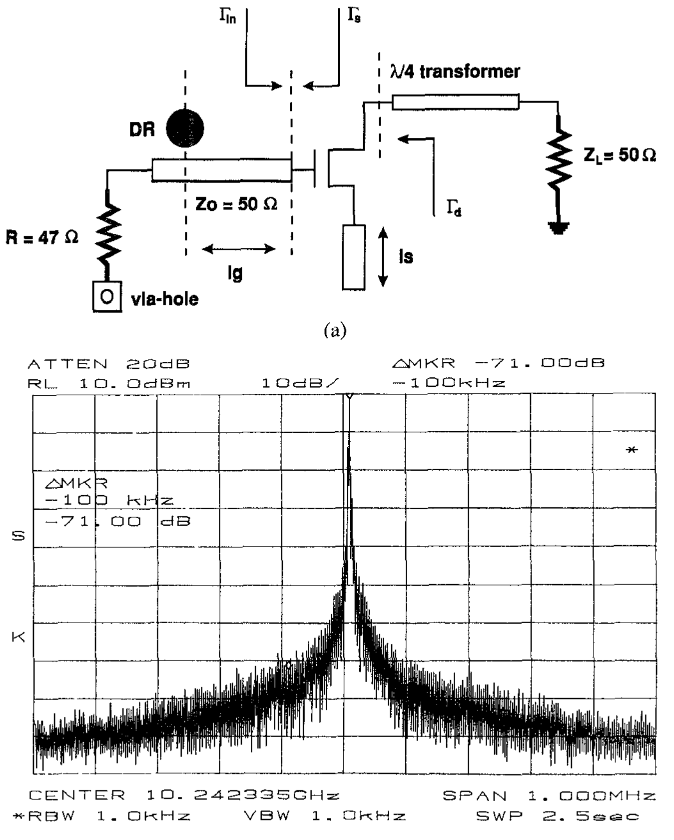
IEEE Log Number 9412085.



(a)

(b)

Fig. 2. (a) Dielectric resonator oscillator circuit schematic. (b) Oscillator output spectrum at 10.24 GHz. Measurement of the phase noise of the oscillator at 100 kHz from the carrier, with a frequency span of 1 MHz and a resolution bandwidth of 1 kHz.

amplifier with a bandwidth BW = 1 kHz, and the minimum radar cross-section of a human target being $\sigma = 0.1$ m^2, our goal was the detection of a moving target at 20 m from the antenna. Under these specifications and using the values in Fig. 1(b), a minimum antenna gain $G_a = 9.1$ dB has been calculated.

A. The Oscillator

Considering the low value of the generated Doppler frequency due to the limited speed of the human target, the short-term stability of the oscillation is to be taken into account first.

A DRO GaAs FET with series feedback oscillator has shown the best characteristics in terms of phase noise, output power and repeatability within the frequency range (Fig. 2(a) and (b)). The synthesis has been performed using linear analysis with the classical two port negative resistance approach [1]–[3]; the EESOF Touchstone (version 3.5) linear simulator was used.

First the potentially unstable condition for the FET ($K < 1$) has been achieved through the classical feedback inductive line to the fet sources. As a second step the resonating circuit has been added on the gate of the device, by setting the position of the DR in order to satisfy the oscillating conditions on the drain port. The oscillator has been designed according to the following equations:

$$\Gamma_{\text{in}} = \frac{1}{\Gamma_s} \tag{1}$$

$$\Gamma_d = S_{22} + \frac{S_{12}S_{21}}{\frac{1}{\Gamma_S} - S_{11}}. \tag{2}$$

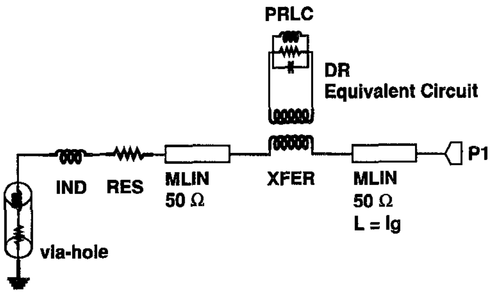


Fig. 3. Equivalent circuit for the DR coupled to the microstrip line. The DR is modelled by a parallel RLC coupled to the circuit by means of a transformer, whose coupling factor is a function of the distance between the DR and the microstrip line.

TABLE I
OSCILLATOR PHASE NOISE MEASUREMENT

MEASURED				CALCULATED
f [GHz]	BW [kHz]	Spacing [kHz]	Power [dBc]	FM Noise [dBc/Hz]
9.9	1	100	-72	-102
10.24	1	100	-71	-101
10.84	1	100	-66.3	-96.3

The output circuit has been then modelled in order to obtain a good matching to 50 Ω. An equivalent circuit model has been used (Fig. 3) to describe the coupling between the dielectric resonator and the 50 Ω microstrip line [4]. The $\text{TE}_{01\delta}$ mode coupling is modelled by the transformer with the turns ratio N that is strongly dependent on the distance between the DR and the line while the RLC parallel circuit represents the resonator with finite Q factor. Measurements obtained by the HP8510C network analyser were used to fit the model for different values of coupling. A parasitic inductance of 0.4 nH due to the resistor and the via-hole was derived from measurements and taken into account in the model.

The length of the 50 Ω line and the series feedback has been determined by introducing the additional constraint $\angle S_{22} = 0$ to force the oscillator to be purely resistive at the output. In this way the condition $X_L = X_{\text{out}}$ between the output reactance of the FET and the load is satisfied, and the matching section consists only of a $\lambda/4$ transformer without any parallel element.

Output power as well as phase noise are significantly affected by the output impedance transformation ratio R_{out}/R_L that has been set to 2.5:1 to reduce the oscillator noise with respect to the usual 3:1 ratio [1], [3] that is generally suggested for maximum power output. Stability of oscillation and output power has been tested in the $-25 \div 60$°C temperature range at different frequencies. A minimum power output of 10 dBm has been measured. Using different DR's the performance of the oscillator in terms of phase noise has been determined (Table I).

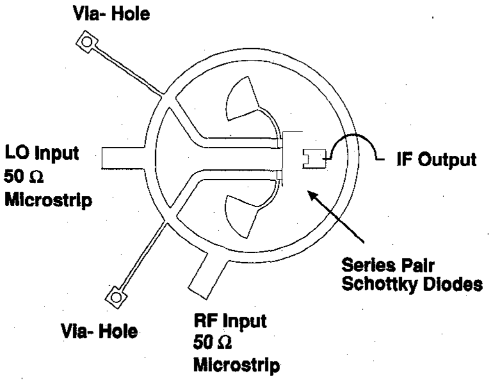


Fig. 4. Rat-race mixer layout.

The behavior of the oscillator is not significantly affected by the reflected signal from the antenna that reaches port 1 of the branch-line.

Mixer: The mixer has been realized using the classical 180° hybrid configuration (Fig. 4) [5], [6] with two Schottky diodes on a single chip, connected to two mutually isolated ports of the hybrid [7], [8]. The total length of the ring is $7/4\lambda$ to allow the insertion of the diodes with their matching networks. The value Z_m of the diode impedance has been derived using the hyperbolic mean between the forward state (Z_{on}) and the reverse state (Z_{off}) [3]

$$Z_{\text{on}} = R_1 + jX_1 \tag{3}$$

$$Z_{\text{off}} = R_1 + jX_2 \tag{4}$$

$$R_m = \left[R_1 R_2\left(1 + \frac{(X_1 - X_2)^2}{(R_1 + R_2)^2}\right)\right]^{1/2} \tag{5}$$

$$X_m = x_1 + R_1 \frac{X_2 - X_1}{R_1 + R_2}. \tag{6}$$

This analysis has been made by means of a commercially available non linear CAD program (EESOF Libra version 3.5) using harmonic balance analysis and optimization.

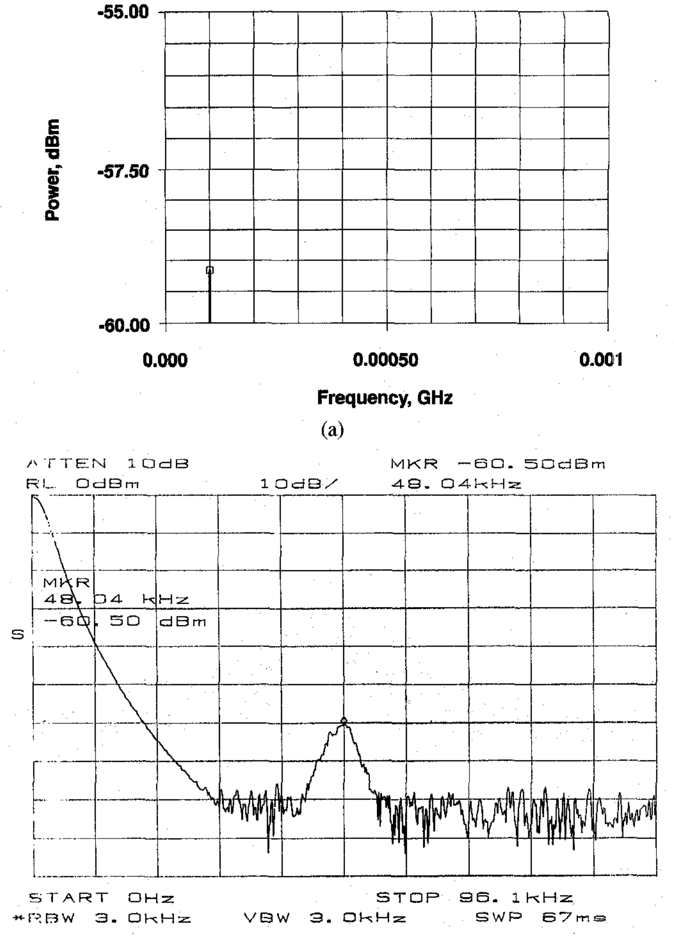
With a −50 dBm RF signal and 7 dBm LO signal a conversion loss of about 8.2 dB is expected. Measurements have been made with −48 dBm at the RF port and +7 dBm at the LO port. Considering a loss of 4.5 dB due to the ring branch-line coupler the results exhibit a good agreement with the simulation (Fig. 5(a) and (b)).

Antenna: A microstrip 4-patch antenna on epoxy glass substrate (FR4) has been designed for this application and it has been characterized through its field pattern, input impedance, gain and beamwidth. The resonators have been modelled using the transmission line approach [10], [11]. The microstrip length L is about half wavelength and depends on the dielectric constant of the substrate material (ε_r).

The input resistance for the single element is $R_{\text{in}} = 118\ \Omega$ which is transformed to $100\ \Omega$ by means of a quarter-wavelength line transformer. This single element is excited in a way that a linearly polarized field is generated, so that a simpler feeding network is needed on the whole array [10].

The width W has been calculated from

$$W = \frac{c}{2f}\left(\frac{\varepsilon_r + 1}{2}\right)^{-1/2} \tag{7}$$



(a)

(b)

Fig. 5. (a) Simulated IF output power spectrum. The spectrum is obtained simulating the circuit with the harmonic balance approach. (b) Measured IF output power spectrum. The spectrum is obtained stimulating the circuit with an external RF signal and evaluating the corresponding IF output signal.

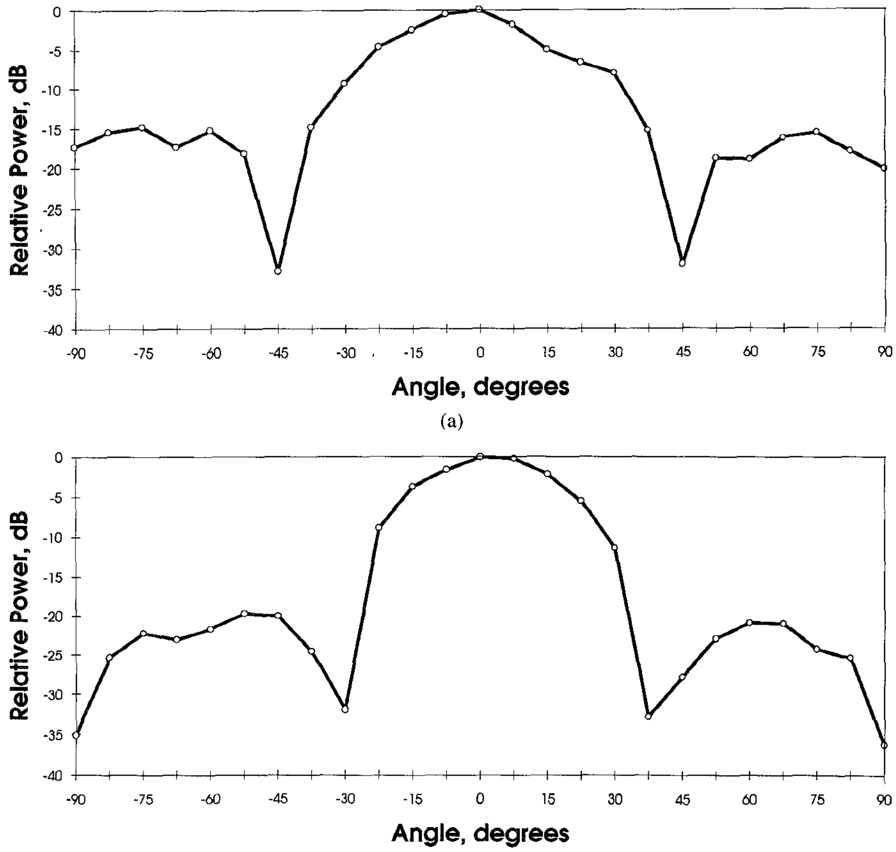
where c is the speed of the light, f is the resonant frequency and ε_r is the dielectric constant of the substrate material. Once W is determined and the effective dielectric constant (ε_e) has been calculated, the length is obtained from

$$L = \frac{c}{2f\sqrt{\varepsilon_e}} - 2\Delta l \tag{8}$$

where Δl takes into account the substrate thickness, the effective dielectric constant (ε_e) and the width W.

The coupling between the elements is less than 20 dB. The radiation pattern of the 4 patch antenna both in the vertical and the horizontal plane is in Fig. 6(a) and (b). The return loss is always better than 15 dB.

On Field Test: The radar was built by simply integrating the active and the radiating subsystems, by means of a via through, and closing the active unit with a conductive case. The system has been tested both in open and closed environment, using a human target. In both cases functional tests have been first carried on, by measuring the maximum detecting distance of the radar. The maximum distance for detection depends on the RF transmitted power, on the receiver sensibility, on the IF section gain and on the Radar Cross Section of the target. In our test set, an IF amplifier with a gain



(a)

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Fig. 6. (a) Measured Vertical Plane antenna radiation field. (b) Measured Horizontal Plane antenna radiation field.

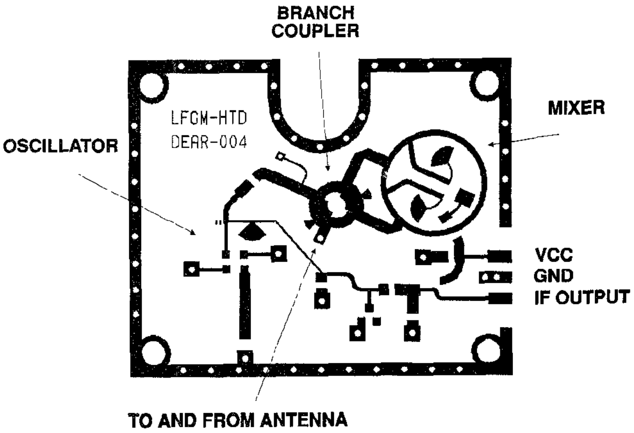

Fig. 7. Active circuit layout. This circuit is integrated with the antenna to build up the complete system; the connection between the two circuits happens by means of a via through which is pointed in the picture.

of 97 dB was used. A voltage comparator discriminates the amplitude level of the detected signal with respect to a preset threshold. The longest distance of detection was measured to be 18 m, with the threshold set at 1.5 V.

We measured also the signal-to-noise ratio, assuming as residual noise the voltage level at the output when no moving target was present. A signal amplitude of 1.8 V and a noise of 180 mV pp were measured. This leads to a signal to noise ratio S/N = 20 dB.

III. CONCLUSION

A X-band Doppler radar operating within the 9.9 ÷ 10.5 GHz frequency range has been presented. Low cost, high repeatability, reduced size and good performance make this product suitable for indoor burglar alarms. The cost of the unit has been kept as low as possible, due to the use of low quality substrates (FR4 for the active and the radiating sub-systems as well) and low cost plastic packaged devices. The design didn't show criticism in terms of repeatability; a 99% production yield characterized the first production run. This system exhibits performance equivalent to other similar designs realized on higher quality substrates while the noise is very much reduced with respect to products based on Gunn diode oscillators. The final release, whose active circuit is presented (Fig. 7) provides a circular slot to eventually house an infrared detector if a double technology system is required. This application agrees with the international recommendation on frequency allocation and maximum radiated field strength.

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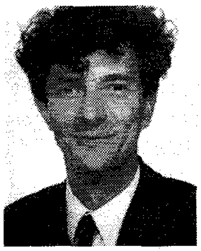
Sergio Battiboia was born November 26, 1964, in Perugia, Italy. He received the Laurea degree in electrical engineering from the University of Bologna in March 1990.

In 1991 he joined Laboratori Fondazione Guglielmo Marconi, where he designed and prototyped microwave circuits for the military and the civil market, and worked on the standardization at the European level of short range communication links for automatic debiting systems. He has also designed a low power X-band radar for indoor burglar alarms. He is also involved in management of the production of this radar equipment. In 1990 he obtained a research grant issued by Fondazione Guglielmo Marconi, Pontecchio Marconi, Italy, and Selenia Spazio S.p.A., Rome, Italy, to carry out a study on the Heart Station for the ITALSAT Satellite System.



Alberto Caliumi was born in Bologna, Italy. He received the degree in electronic engineering from the University of Bologna in 1985.

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Leonardo Masini was born in Rimini, Italy, in 1966. He received the Ph.D. degree in electronic engineering in 1993 from the University of Bologna.

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