MICROWAVE SHORT-RANGE INTERFEROMETRIC RADAR

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ABSTRACT

A contactless short range sensor based on microwave interferometry is able to determine the distance to a reflecting area which is perpendicular to the bore sights of the transmitting and receiving antennas. If this condition is not verified, a second sensor using the same principle, measures the angle of deviation and consequently authorises level measurement. The exploited interferences are constructed by making the complex cross correlation product between the different received signal by mean of a complex correlator which provides I-Q data. The paper presents the principle of a level measurement or anti collision and an inclinometer processes and discuss experimental results obtained at both frequencies 2.45 and 10 GHz. Are also discussed some improvements of the complex correlator.

Keywords : microwave interferometry, short range sensing, complex correlator, level measurement, inclinometer

INTRODUCTION

Needs of contactless devices in robotics, automotive and industrial fields are still addressed. Answers generally given utilise heavy systems such as FMCW and Doppler radar that are not convenient for short range domain. Alternative and complementary solutions using microwave interferometry techniques have allowed applications such as non destructive control [1], velocity [2] and position [3] measurement, anti collision or level measurement [4] where prototypes, using low cost components, have been achieved at frequencies of 2.45 and 10 GHz.

The purpose of this paper is the presentation of a microwave short-range interferometric radar, working for distances between several decimeters and several tens of meters and operating in severe environments (clouds, rain, snow, smoke or dust). This sensor, by taking advantages from information contained into the phase difference, is able to determine both the distance to a reflecting panel and the angle of deviation of this panel from the bore sights of the antennas. Note that the angle measurement has already been measured by exploiting others principles such as the dependence of the conductivity on the angle of inclination [5] or by using acoustic waves [6].

After explaining the basic principle of this interferometric method, we discuss the both processes level measurement and inclinometer. Experimental results obtained by a first prototype has pointed out that improvements are required in applications where the accuracy is needed. A such development corresponding to a second prototype of the complex correlator is discussed.

PRINCIPLE

As shown in figure 1, a monochromatic signal (wavelength λ) is transmitted by the antenna A at co-ordinates (x_0,y_0). Four similar receiving antennas (BCDE) are disposed at the vertexes of the square BCDE. The bore sights of the five antennas are oriented according to the 0z axis, with 0xyz a trirectangular.

The reflected signals are simultaneously received by the both pair of antennas (B,D) and (C,E) and treated by two complex correlators (or I-Q demodulators) providing each one two equal amplitude signals (eventually modulated by antennas pattern) that are in phase quadrature (I-Q data). The four outputs signals are depending on the phase differences Φ_{BD} and Φ_{CE} defined as follow :

$$\Phi_{BD} = \frac{2\pi(d_2 - d_1)}{\lambda} \qquad \Phi_{CE} = \frac{2\pi(d_4 - d_3)}{\lambda} \tag{1}$$

with (d_1, d_2) and (d_3, d_4) the paths followed by the signals from the virtual source A' to the different receiving antennas, such as shown in figure 1 i.e.

($d_1 = \overline{A'B}, d_2 = \overline{A'D}, d_3 = \overline{A'C}, d_4 = \overline{A'E}$). These phase differences are depending on parameters such as the position and the velocity of the transmitter, the distance h and the angles of inclination α and β, defined as $\alpha = B0B' = D0D', \beta = C0C' = E0E'$ respectively in the planes x0z and y0z. Therefore it seems possible to reach desired parameters by inversing relations (1).

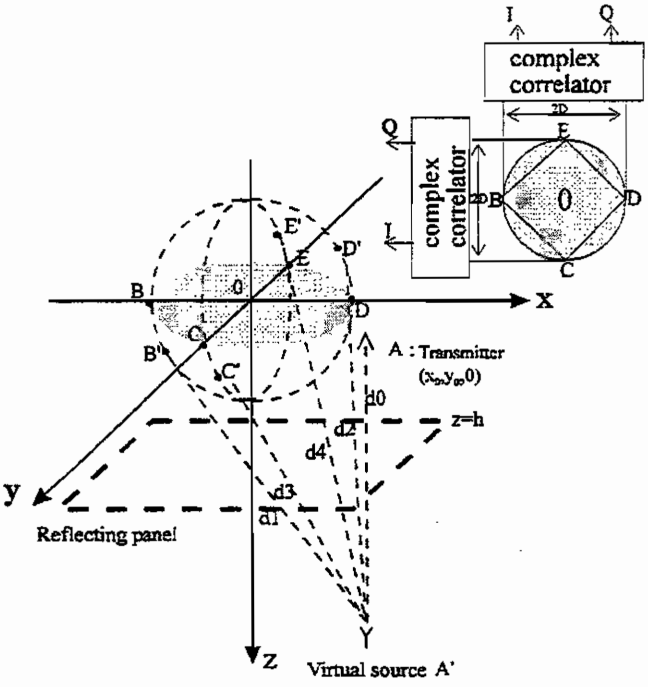

Figure 1. Principle of interferometric radar

Preliminary to the illustration of this principle consisting in the presentation of both applications, level measurement and inclinometer, let us define the main features of this system. The whole signals outputs are conditioned by the known parameters as the wavelength λ, the baseline 2D i.e. the distance separating receiving antennas forming the pair and the co-ordinate of the transmitter. We also consider that far field conditions and thus ray mode transmission are assumed and finally that antennas are their phase centers on ABCDE (BD and are located respectively on the axis of rotation 0x and Note that since this measure technique is based on the exploitation of the phase difference, precautions must be taken to avoid ambiguity.

Level measurement

The first process we discuss is the level measurement or anti collision. In this case the angles of inclination α and β are considered null. For clarity we reason with the followed hypothesis : the transmitter is located on the 0x axis at abscissa x_0 and thus we consider only the change in the phase difference Φ_{BD} when the distance h varies. Let us consider that the reflecting area, first at a distance greater than several meters, draws nearer to the system. Φ_{BD}, first equal to several tens of degrees, increases slowly and, for the first time, becomes equal to $\Phi_1 = 90°$, and later on to $\Phi_2 = 180°$, $\Phi_3 = 270°$ and $\Phi_4 = 360°$. These events occur when the distance h becomes equal to values we call respectively h_1, h_2, h_3 and h_4. The anti collision process is based on these particular values of Φ_{BD}, which can be reached only in condition that the distance h decreases. The threshold distances h_1, h_2, h_3 and h_4 are defined by the experimental conditions i.e. by λ, x_0 and 2D.

We present, for example, in figure 2a the computed and figure 2b the smoothed experimental I-Q data versus h for F=10 GHz, x_0 = 20 cm and 2D = 10 cm.

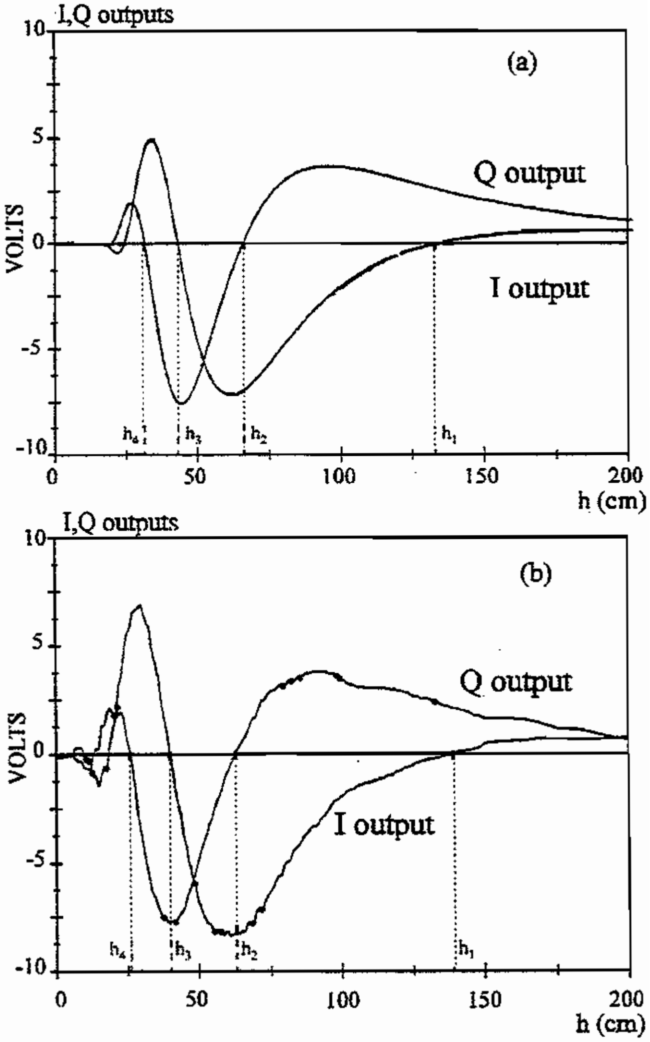

Figure 2. I-Q signals versus the distance h
for α=β=0, 2D=10 cm, x_0=20 cm and F=10 GHz
(a) computed, (b) measured

Therefore we point out the possibility to detect the threshold distances even in presence of clutter. By inversing relation (1) we show easily that the distance h is measurable (figure 3) considering the approximate linear relationship obtained, when the baseline 2D is negligible respect to the distance h and expressed as :

$$h \cong \frac{2\pi D x_0}{\lambda \Phi_{BD}} \qquad (2)$$

Experimental results such as shown in figures 2 and figure 3 point out that the maximum error is better than 10%. However this accuracy is not convenient for particular applications and thus the exploitation of the perpendicular reflected signal along the path d_0 is required.

In this case the useful interferences, hich allow the determination of the distance h, are constructed by making the cross correlation product between reflected signals and the signal provided by the antenna mismatch [7]

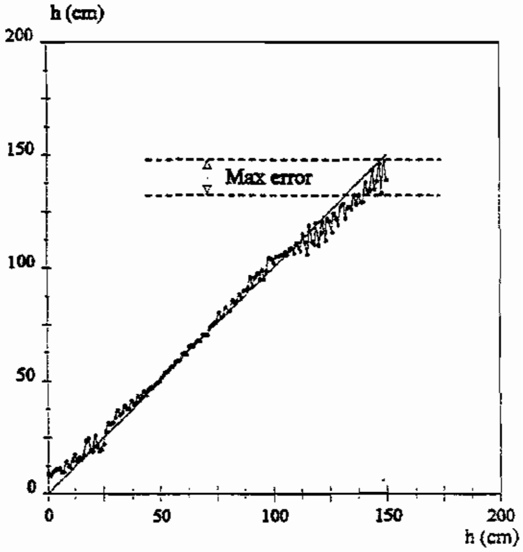

Figure 3. Inversion of relation 1 by treating I-Q signals obtained in figure 2b and using relation (2)

The both measurement of threshold distances and the distance h are affected by the inclination of the reflecting panel and then justify the following study which consists in the presentation of a second application concerning an inclinometer where recent results are obtained.

Inclinometer

A second application is dedicated to the determination of the inclination angle α when the angle β is maintained null. In this case the source is in the center of the square BCDE at co-ordinates (0,0), and only a pair of receiving antennas (BD) is required. As previously, we show that the I-Q data are changing when the reflecting panel is not perpendicular to the bore sights of antennas. For $\alpha=0$, the phase difference is null. For small inclination angles, the relationship between phase difference and angle is linear and depends only on parameters such as the wavelength and the baseline.

When the reflecting area or the receiver rotates simultaneously around 0y axis by angle α and around 0x axis by an angle β, the system requires a second pair of antennas (CE).

We first consider the square BCDE to be parallel to a plane reflecting area located at a distance z=h. In this case the phase shift Φ_{BD} and Φ_{CE} between B and D, are zero. Any deviation of an angle between antennas bore sights and perpendicular to the reflecting area (0BCDE are now located respectively at 0B'C'D'E') (figure 1) is associated to a variation of the mentioned phase shifts such as defined in relation (1). It seems obvious that the measurement of the phase difference provides an efficient indicator of horizontability because it becomes different to zero when the reflecting panel is not parallel to the plane formed by the square BCDE. In practice, the distance $2D = \overline{BD} = \overline{CE} = \overline{B'D'} = \overline{C'E'}$, is much smaller than the distance h. Therefore the relationship between the phase differences Φ_{BD} and Φ_{CE} and angles of inclination α and β can be written such as follow :

$$\begin{pmatrix} \Phi_{BD} \\ \Phi_{CE} \end{pmatrix} = \frac{4\pi D}{\lambda} \begin{pmatrix} \sin(\alpha) \\ \sin(\beta) \end{pmatrix} \qquad (3)$$

Note that the relationship (3) does not depend on the distance h and thus α and h can simultaneously be measured. Note also that the relation (3) can suffer from ambiguity, therefore, the angles of inclination are determined inside a dynamic range such as the measured phase differences are included inside the interval $[-\pi,\pi]$. This condition which involves the decreasing of the ratio (D/λ), to obtain a large dynamic range (figures 4), is not convenient for assuring a good accuracy. A compromise solution should take into account the kind of application. Note that the dynamic range is also affected by the width of the main lobes of the antennas and by the required signal to noise ratio.

Figures 4a and 4b shows calculated I-Q data versus the angle α at F=2.45 GHz with $2D/\lambda=2$ and at F=10GHz, for $2D/\lambda=3$. The angle β is maintained equal to zero. We observe that the number of fringes, parameter which conditions measurements without ambiguity and the accuracy (related to the slope) increase whith the ratio $2D/\lambda$.

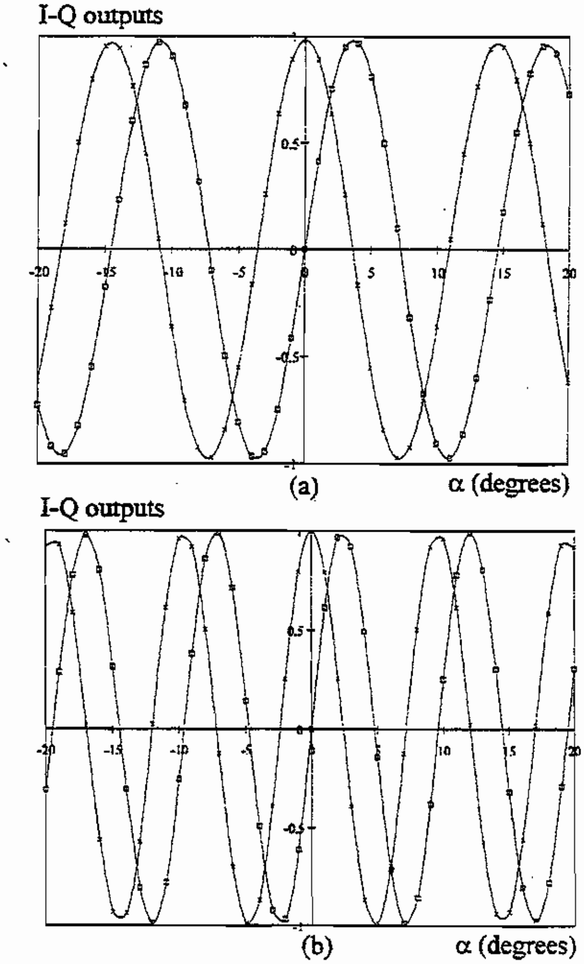

Figure 4. Computed I-Q Signals versus angle of deviation α for both configuration
a) F=2.45 GHz, $2D/\lambda=2$
b) F=10 GHz, $2D/\lambda=3$

EXPERIMENTAL SET-UP

From the relation (1), a classical process based on PLL devices using varactor is able to provides output signal proportional to the phase difference. It can consequently allow the determination of the considered angle or the distance h by measuring the suitable phase shift to be introduced electronically to maintain the output signal null. This feedback method can be replaced by a more attractive and simple one based on the real time measurement of the phases difference. In this case the signals received by the array of a couple of antennas are treated by a complex correlator in order to provide I-Q data. The exploitation of theses signals which are equal amplitude (modulated by the antenna pattern) and phase quadrature allows the determination of the phase difference without ambiguity in a suited situation. Recent results concerning the inclinometer are discussed here after

A transmitter-receiver, such as mentioned in this paper, has been achieved both at 10 GHz and 2.45 GHz with a transmitted power of 10 dBm. At the frequency of 10 Ghz, it consists mainly of commercially available X-band pyramidal horns, with a moderate gain 16 dB and a VSWR less than 1.2 while the system operating at 2.45 GHz is composed of circulary polarised patch antenna with the follow features : axial ratio less than 3dB, $|S_{11}| = -14\text{dB}$ and a cross polarisation rejection better than 14 dB.

Received signals are treated by the complex correlator which provides I-Q data. A first prototype have already been achieved and used for the level measurement. It is an hybrid circuit implanted on Duroïd (ε_r=10.5, h=635 µm), including 90° hybrid couplers, delay line, square law detectors and D.C. differential amplifiers. In these preliminary experiments, the reflecting object is a flat metallic surface (area 80 cm * 80 cm) rotating around an axis perpendicular to the bore sights of the antennas. The dimensions of the reflecting panel regarding the distance h are such as edge effects can be neglected.

Experiments have been carried out for different values of $2D/\lambda$ demonstrating the validity of the method, and showing that, at the frequency 2.45 GHz the measurement of the angle α from experimental I-Q data (figure 5) can be operated without ambiguity in the range $\pm 10°$ and with an accuracy better than $\pm 0.8°$ such as shown in figure 6.

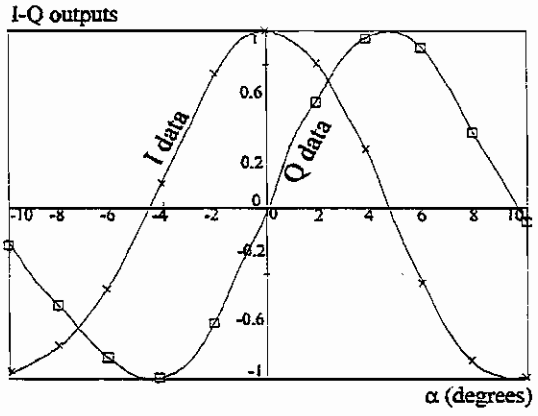

Figure 5 : Experimental signals I-Q versus angle α for F=2.432 GHz and 2D = 36 cm

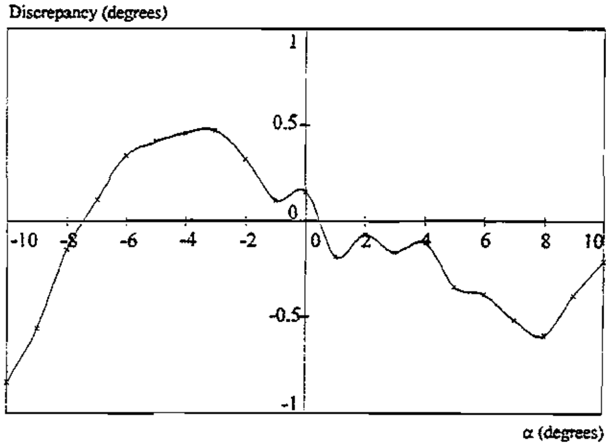

Figure 6. Angle error diagram

Experimental results obtained at the frequency 10 GHz are summarised in table 1. They show the compromise which exists between accuracy and dynamic range.

Table 1. Dependence of the maximum error on the operating range for both configurations

	operating range	
	-25°<α<+25°	-10°<α<+10°
configuration 1 2D=10cm, F=10GHz	3.4%	0.7%
configuration 2 2D=20cm, F=10GHz	3.9%	1.3%

We can summarise the capability of the process in the following way. This inclinometer radar is able to generate a warning signals when the reflecting object is not parallel to the axis of the receiver. Therefore it seems suitable for application in automotive and robotics fields.

IMPROVEMENT OF THE PROTOTYPE

For the both applications the system here described is affected by multipath effects and the phase error of the complex correlator associated to poor signal to noise ratio occuring when the angle α or the distance h increases. As a matter of fact the shape of the radiation pattern of transmitting and receiving antennas modulate the received signals and thus may reduce considerably their amplitude.

Multipath effects are circumvented by using circulary polarised antennas while the improvement of the complex correlator features is submitted to the definition of a second prototype. We present now the last version of the complex correlator which is used in an other application which treats the remote positioning problem.

The performances to be reached by the prototype are to provide I-Q signals with a minimum phase error in a large dynamic of input signals. Phase error minimisation is obtained by trimming, by software, the both amplitude and phase of I-Q signals while the large dynamic utilises a hardware solution which is driven by a microprocessor. Figure 7 shows the basic scheme of such a prototype. The device utilises conjointly microwave components, analogue and numerical circuits (such as locking system) and performs the complex cross correlation product of input signals $\bar{A}$ and $\bar{B}$.

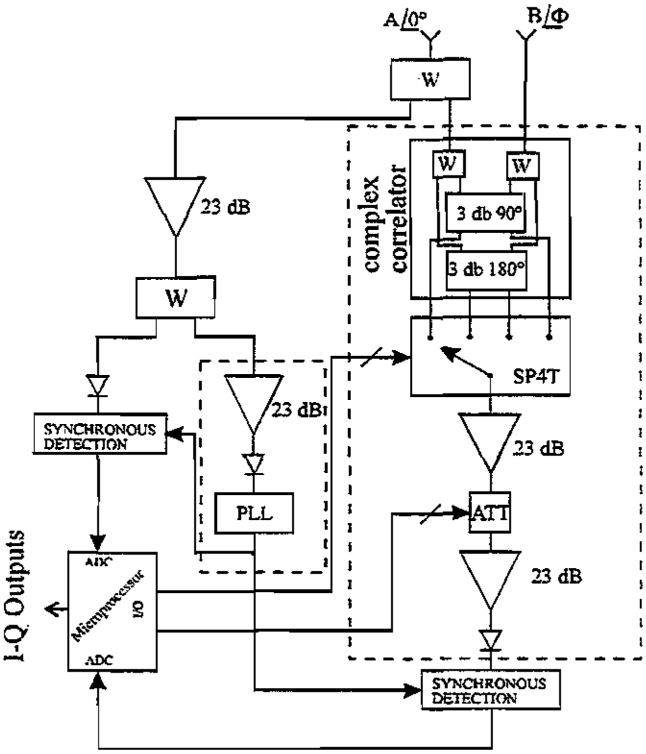

Figure 7 : Synoptic of the complex correlator

The microwave sub system consists of a complex correlator, formed by two power dividers (W) and two hybrid couplers (3dB, 90° and 3dB, 180°), where outputs are connected via a SP4T to an automatic control gain device formed by two amplifiers, a programmable attenuator and a square law detector. For input levels varying from -85 dBm to -35 dBm, attenuator is programmed to maintain the level on the detector such the square law detection is verified and thus minimises imperfections caused by undesirable non linearity of which the diode is the seat.

Inputs signals $\bar{A}$ and $\bar{B}$ are modulated at 100 Khz. The locking system is made of a microwave amplifier and a PLL which extracts clock signal to achieve synchronous detection.

Characterisation of the prototype is presented figure 8 where are shown the comparison between experimental I-Q constellation measured at 2.45 GHz with an input power equal to -63 dBm and an ideal case. The performances reached exhibits a phase error less than ± 2° inside a dynamic range of 50 dB.

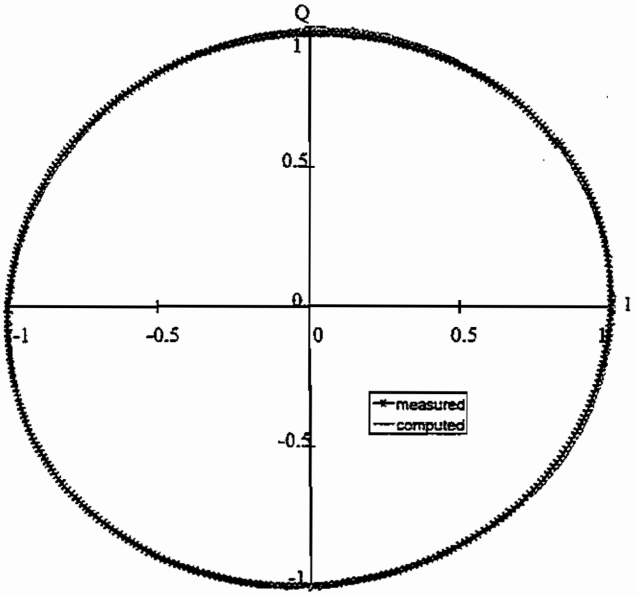

Figure 7. Experimental I-Q constellation compared to ideal case for F=2.45 GHz, Pin=-63 dBm

CONCLUSION

This paper describes the principle of a short-range interferometric radar. The interest of microwave interferometry combined to I-Q detection leads to the measuring of the distance to a reflecting area and its horizontability. Moreover, it has to be noticed that different values of the range of deviation angle can be achieved as a function of the requirements of the application. This adjustment is made by a convenient choice of the experimental parameters D and λ.

Another interest of the method is that it needs only a C.W. source and a few low-cost microwave devices. Performances reached by the last prototype are compatible with the most interested applications and thus encourage to face its integration.

REFERENCES

1. T.Lasri et al, "A low cost microwave system for non destructive control of textile webs,"Journal of Microwave Power and Electromagnetic Energy, Vol. 31, n° 2 122-126, 1996

2. A. Benlarbi-Delaï, D. Matton and Y. Leroy,"Position, Velocity Profile Measurement of a Moving Body by Microwave Interferometry," IEEE Trans. Instrum. Meas., Vol IM 39, 632-636, august 1990.

3. A. Benlarbi-Delaï, D. Matton and Y. Leroy, "Short-Range Two Dimension Positioning by Microwave Cellular Telemetry," IEEE MTT : vol. 42, N°. 11, 2056-2062, november 1994.

4. A. Benlarbi-Delaï and Y. Leroy, "A Novel Short-Range Anti collision Radar," Microwave and optical technology letters Vol. 7, N°11, 519-521, august 5 1994.

5. HL. Planar Technik Inclination sensors - New persepctives for the automotive sector. GmbH, D-44227 Dortmund Hauert 13, Germany

6. D. Marioli et al.,"Ultrasonic distance measurement for linear and angular position control," IEEE Trans. Instrum. Meas., Vol IM 37, 578-581, December 1988.

7 A. Benlarbi-Delaï, J.P. Covillers, Y. Leroy "Dual-Mode Anticollision Short-Range Radar".EuMC, 5-8 septembre 413-418, 1994 Cannes.