# 24 GHz Low-Cost Doppler Speed-over-Ground Sensor with Fundamental-Frequency PHEMT-DRO

by Heide, P. / Schubert, R. / Mágori, V. / Schwarte, R.[1]

Siemens AG, Corporate Research and Development, Munich (Germany)
[1] University of Siegen, Institut für Nachrichtenverarbeitung, Siegen (Germany)

## ABSTRACT

A 24 GHz high-performance Doppler sensor for non-contact measurement of vehicle speed and position is reported. The compact dimensions and the economical design make the sensor ideally suited for automotive applications. A special feature is the 24 GHz fundamental-frequency dielectric resonator oscillator employing a low-cost packaged HEMT. An excellent phase-noise behavior and good temperature stability are achieved due to higher-order mode operation of the dielectric resonator. The new Doppler sensor provides high reliability and gives excellent measurement results in both car and train tests.

## INTRODUCTION

With the increasing use of advanced vehicle-control and navigation systems, the interest for a precise non-contact measurement of speed and position of a vehicle has been stimulated [1]. Due to the robustness of microwaves against changing environmental conditions, radar sensors are superior to sensors employing optical or ultrasonic principles. Microwave sensors operating in the 24 GHz band provide high sensitivity and excellent reliability at low costs.

For the measurement of speed $v_X(t)$ and position x(t), a microwave beam is emitted obliquely to the ground (Fig. 1). A small part of the wave is scattered back into the antenna by statistically distributed scattering centers. Due to the Doppler effect, the frequency of the back-scattered signal is shifted in frequency proportional to the vehicle speed. The Doppler signal u(x) is obtained by rectifying the standing-wave signal existing between the oscillator and the antenna by means of a schottky diode (Fig. 2). To a first approximation, counting the periods of u(x) gives a measurement value for the driven distance, wheras its frequency is proportional to the speed. Despite of the statistical fluctuations of the Doppler signal, elaborate signal evaluation methods estimate the true values for speed and displacement within an error bound of less than 1%.

## DIELECTRIC RESONATOR OSCILLATOR DESIGN

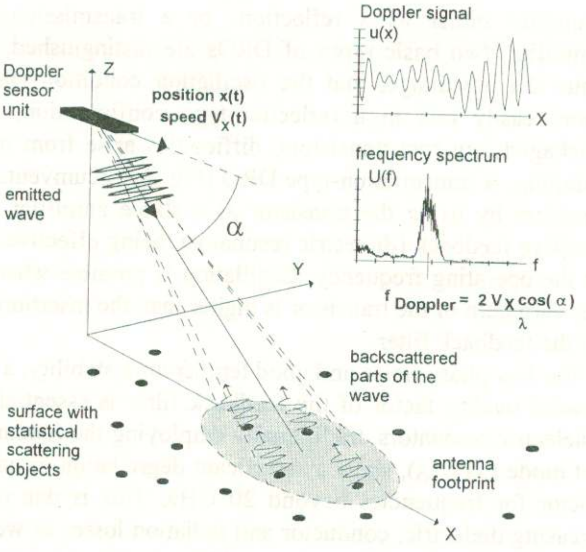

Fig. 1: Principle of non-contact, speed-over-ground measurement.

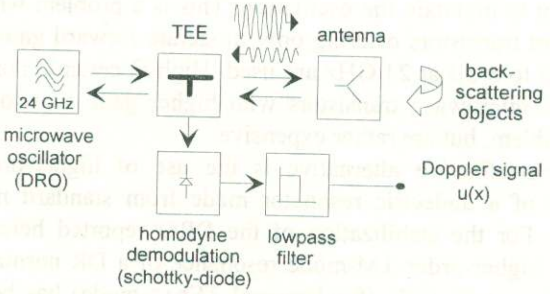

Fig. 2: Doppler sensor with schottky-diode demodulator.

The key component of a Doppler sensor is the microwave oscillator. So far, cost-effective dielectric resonator oscillators (DROs) at 24 GHz have been realized as frequency-doubling oscillators [2], but these oscillators radiate significant amounts of spurious output power at 12 GHz. Recent advances in High Electron Mobility Transistors (HEMTs) make the employment of low-cost packaged HEMTs for fundamental-frequency DRO operation at 24 GHz practical. The oscillation in a DRO is maintained in a closed feedback loop which consists of an active device (transistor) amplifying the microwave signal and a filter (dielectric resonator) determining the frequency. With respect to the use of the

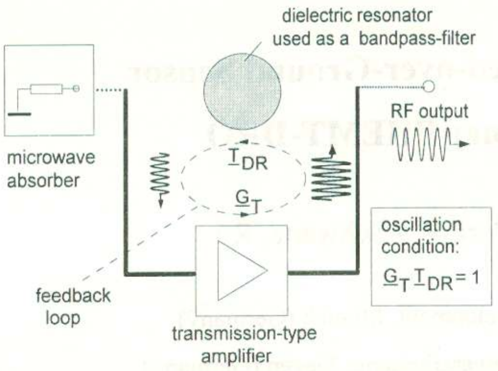

Fig. 3: Structure of the transmission-type oscillator.

transistor either as a reflection- or a transmission-type amplifier, two basic types of DROs are distinguished. Despite the advantage, that the oscillation condition can be more easily met in a reflection-type configuration, with packaged low-cost transistors, difficulties arise from mode jumping. A transmission-type DRO (Fig. 3) circumvents this problem by using the transistor as a stable amplifier with positive feedback (dielectric resonator), being effective only at the operating frequency. Oscillation is possible when the forward gain of the transistor is higher than the insertion loss of the feedback filter.

For low phase-noise and good temperature stability, a high loaded quality factor of the feedback filter is essential [3]. Dielectric resonators, traditionally employing the fundamental mode ($TE_{01\delta}$), show a significant degradation in quality factor for frequencies beyond 20 GHz. This is due to increasing dielectric, conductor and radiation losses as well as the small resonator dimensions with respect to a microstrip line [4]. Weaker coupling of the resonator improves the Q-factor, but simultaneously leads to an increase in the filter insertion loss, which must be compensated by higher transistor gain to maintain the oscillation. This is a problem when low-cost transistors offering only moderate forward gain of about 6 to 8 dB at 24 GHz are used. High-Q ceramic materials or microwave transistors with higher gain may solve the problem, but are rather expensive.

A cost-effective alternative is the use of higher-order modes of a dielectric resonator made from standard materials. For the stabilization of the DRO reported here, a strong higher-order TM-mode resonance of a DR normally operating at 12 GHz (fundamental $TE_{01\delta}$-mode) has been employed (Tab .1: DR2). This sharp resonance line has been identified as the $TM_{021+\delta}$-mode [5] and can be excited effectively when the dielectric resonator (DR2) is mounted in an upright position (Fig. 4). For two different dielectric resonators (DR1, DR2) operating in a 24 GHz microstrip bandpass-filter configuration, the loaded quality factors, which can be achieved in fundamental-mode (DR1) and $TM_{021+\delta}$-mode (DR2) have been determined. From the width of the measured resonance curves (Fig. 5), the corresponding loaded Q-values ($Q_L$) have been calculated for an insertion loss of $S21_{max}(f_0) = -8dB$.

The results demonstrate that a substantial enhancement (about one order of magnitude) of the loaded Q-factor is possible, when a higher-order mode is used instead of the $TE_{01\delta}$-mode. This leads to remarkable cost savings because one can use cost-effective packaged transistors and standard dielectric resonators, such as DR2, instead of employing expensive components. Due to larger dimensions, those resonators and packaged transistors are easier to handle in the manufacturing process.

Table 1: Data of investigated dielectric resonators [6].

| DR | mode used | D [mm] | h [mm] | $\varepsilon_r$ | $Q_0 \cdot f$ [GHz] | material |
|---|---|---|---|---|---|---|
| 1 | $TE_{01\delta}$ (fundamental) | 2.7 | 1.1 | 29 | $100 \cdot 10^3$ | Ba(Zr,Zn,Ta)$O_3$ |
| 2 | $TM_{021+\delta}$ (higher-order) | 4.9 | 2.0 | 38 | $50 \cdot 10^3$ | $(Zr,Sn)TiO_4$ |

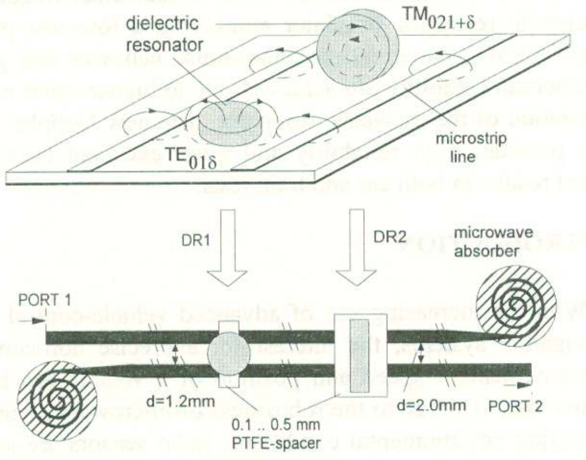

Fig. 4: Microstrip bandpass-filter etched on 0.25mm thick RT/Duroid soft substrate (during the measurement of S21(f) only one dielectric resonator is present).

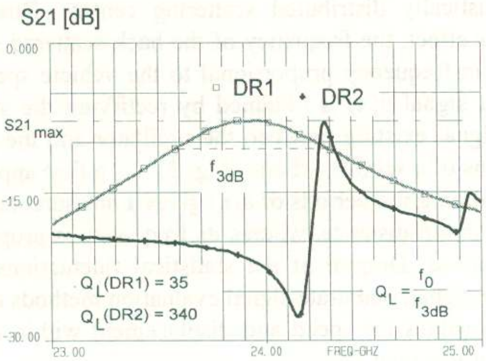

Fig. 5: Measured resonance curves S21(f) of the microstrip bandpass-filter using DR1 and DR2.

## DOPPLER SENSOR UNIT

Employing a packaged HEMT, a transmission-type fundamental-frequency DRO at 24 GHz has been realized in microstrip hybrid technology on 0.25 mm thick RT/Duroid 5880 soft substrate. The CFY67 [7], which is a pseudomorphic AlGaAs/InGaAs HEMT - commercially available in a ceramic transistor housing - is very suitable for this oscillator design. With DR2, operating in $TM_{021+\delta}$-mode (Tab.1), the DRO shows an excellent phase-noise performance of about -95 dBc/Hz at 100 kHz offset from the carrier frequency (Fig. 6). The maximum temperature deviation of the oscillation frequency is +9ppm/°C in the range from -40 to +100°C (using a resonator with temperature coefficient +8 ppm/°C). The oscillator output power is about +10 dBm.

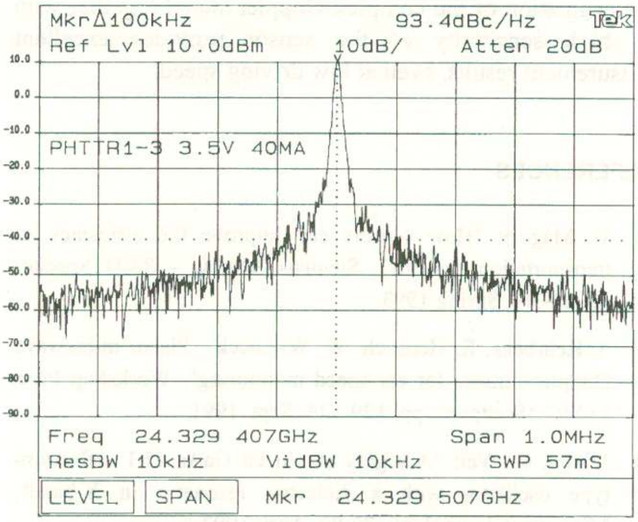

Fig. 6: Typical frequency spectrum of the fundamental-frequency DRO employing a packaged HEMT and the higher-order $TM_{021+\delta}$-mode of the dielectric resonator (DR2).

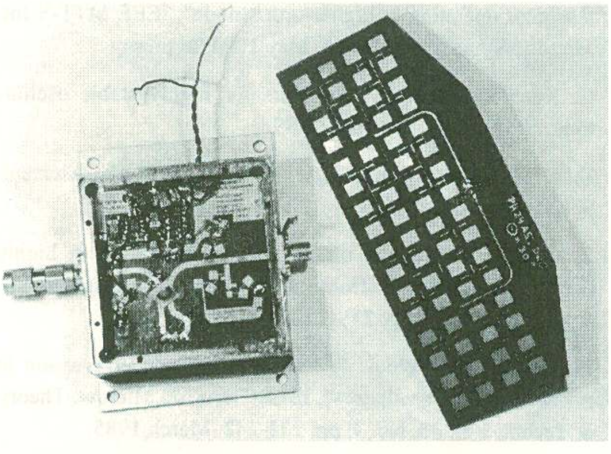

Fig. 7: Low-cost, compact 24 GHz Doppler sensor-unit with fundamental-frequency dielectric resonator oscillator and "Janus"-type microstrip patch-antenna suitable for automotive applications.

The sensitivity of a Doppler sensor is considerably affected by the low-frequency noise of the microwave FET used in the oscillator. Microwave FETs exhibit 1/f flicker-noise as well as generation/recombination-noise at frequencies up to the MHz region [8], which is up-converted to near-carrier phase- and amplitude-noise sidebands by device nonlinearities [9]. Recently, the noise properties of different types of microwave transistors (MESFET, HEMT, PHEMT) have been investigated [10]. A non-representative number of devices is measured, but from the results it can be assumed, however, that the LF-noise properties of modern pseudomorphic HEMTs - showing the lowest LF-noise in [10] - are equivalent to classical MESFET devices. Moreover, low-frequency oscillator-noise not only depends on the transistor type and manufacturing process but also to an considerable extend on the transistor bias and the topology of the oscillator.

In short-range Doppler measurements, phase fluctuations of the oscillator are not of main concern. However, for a reliable steady-state oscillation and good temperature stability, the investigated high-Q $TM_{021+\delta}$-mode is used, which inherently provides low oscillator phase-noise. The sensitivity of our Doppler sensor system with fundamental-frequency PHEMT-DRO has been compared in speed-over-ground measurements with another one, utilizing a frequency-doubling MESFET-DRO [2]. Both oscillators provide almost the same phase-noise and output power. The signal to noise ratio of the Doppler signals, obtained from a rotating disc with scattering objects, proved to be almost the same for both sensors, when the same sensor antenna is used.

This is an important result, demonstrating the feasibility of a 24 GHz fundamental-frequency DRO with equivalent RF and LF performance at the same cost as a frequency-doubling oscillator. Additionally, unwanted spurious output at 12 GHz can principally be avoided. Figure 7 (left) shows the compact Doppler sensor-unit comprising the 24 GHz fundamental-frequency DRO, a homodyne Doppler signal detector and biasing circuitry. Shown on the right of Fig. 7 is a so-called "Janus"-type patch-antenna, which has two symmetrical, narrow beams oriented in forward and reverse direction in respect to vehicular motion. This allows the compensation of tilt-angle errors; important in automotive applications.

## PRACTICAL DOPPLER MEASUREMENTS

The Doppler sensor has been tested extensively on both car and train. Even under rough environmental conditions, no failure of the system has been observed. Figure 8 shows a sensor box, installed on a car. It contains the Doppler sensor-unit as seen in Fig. 7, but has a comb-line array antenna [2] with a single, narrow beam oriented in the reverse driving direction of the car. For the determination of the direction of motion, a second, orthogonal Doppler signal channel v(x) has been implemented. Both Doppler signals u(x), v(x) represent the components of the complex Doppler signal vector $\underline{d}(x)=u(x)+jv(x)$ shown in Fig. 9. To a first approximation, each driven distance of $\Delta x = \lambda / 2 \cdot \cos(\alpha)$

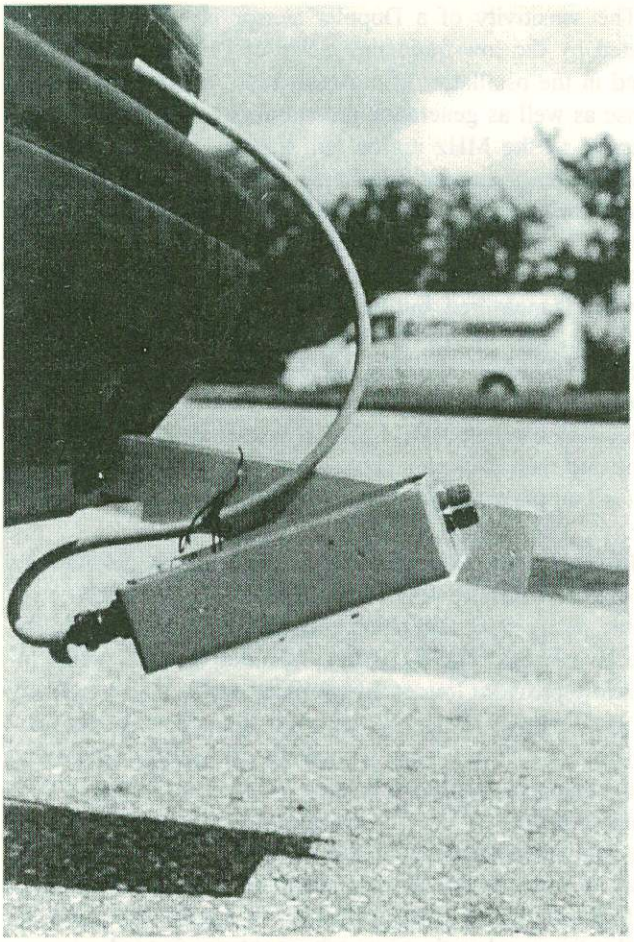

Fig. 8: Sensor box mounted on car. A comb-line array patch-antenna radiates a single beam in reverse direction. The angle α of the emitted beam (see Fig. 1) has been varied.

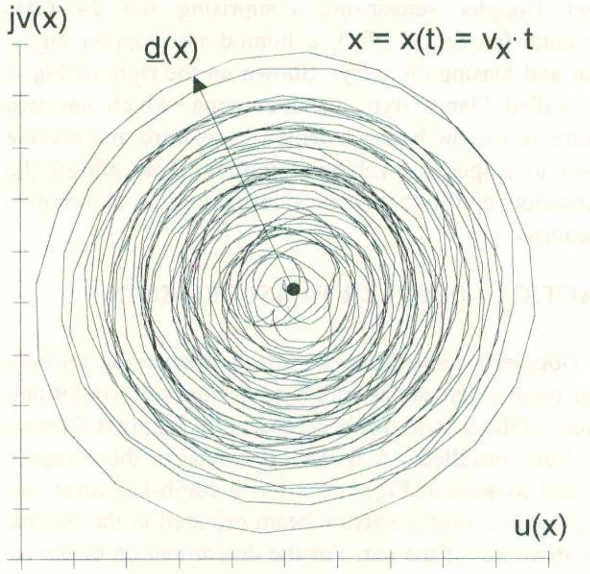

Fig. 9: Typical complex Doppler signal $\underline{d}(x) = u(x) + jv(x)$ measured on car (see Fig. 8) with $\alpha = 45°$ at a speed of $v_x = 50$ km/h.

corresponds to a full rotation of $\underline{d}(x)$ in clockwise or counterclockwise direction (depending on the direction of vehicular motion). The Doppler signal $\underline{d}(x)$ has a good signal to noise ratio. Small deviations in vehicle position in the order of a wavelength and even the condition "no motion" can be detected.

## CONCLUSION

A compact, low-cost Doppler sensor-unit at 24 GHz for non-contact measurements of speed and position - ideally suited for automotive and railway applications - has been built. The high stability of the fundamental-frequency dielectric resonator oscillator employing a higher-order resonator-mode results in an enhancement of both the RF-performance and the reliability of the microwave oscillator. The evaluation of the complex Doppler signal together with the high sensitivity of the sensor provides excellent measurement results, even at low driving speed.

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