CODED 24 GHZ DOPPLER RADAR SENSORS: A NEW APPROACH TO HIGH-PRECISION VEHICLE POSITION AND GROUND-SPEED SENSING IN RAILWAY AND AUTOMOBILE APPLICATIONS

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ABSTRACT

Coded 24 GHz Doppler sensors have been realized to perform high-precision non-contact vehicle position and speed measurements. Encoding the radar signal with a spread-spectrum code is the key to a significantly enhanced sensitivity combined with a range selectivity of the sensor. The novel system concept establishes a high-performance low-cost vehicle Doppler radar system with very high measurement accuracy suitable for automotive and railway applications.

INTRODUCTION

With dramatically increasing traffic congestion, the need for higher traffic efficiency and increased driver safety becomes a prime concern [1]. By measuring the true ground-speed with Doppler radar sensors, the capabilities of advanced vehicle control systems (e.g. anti-slip control and anti-lock brake systems) can be enhanced in both automotive and railway applications. Furthermore, precise measurements of the relative position between fixed reference points are enabled. This paper discusses novel inexpensive vehicle Doppler radar sensors with spread-spectrum coding. The coding leads to a very high signal-to-noise ratio and the capability to focus the Doppler signal evaluation to a certain measurement distance.

24 GHZ OSCILLATOR / DETECTOR MODULE

The basic component of the Doppler sensor is a highly stabilized 24 GHz fundamental-frequency dielectric resonator oscillator (DRO). The use of a higher-order mode of the dielectric resonator has led to a new type of DRO [2] with high spectral purity (phase noise level: -95 dBc/Hz @ 100 kHz) and good temperature stability (+10 ppm/K). Adding a schottky diode detector as a homodyne receiver and a patch antenna [3], a low-cost compact CW Doppler sensor has been built (fig. 1).

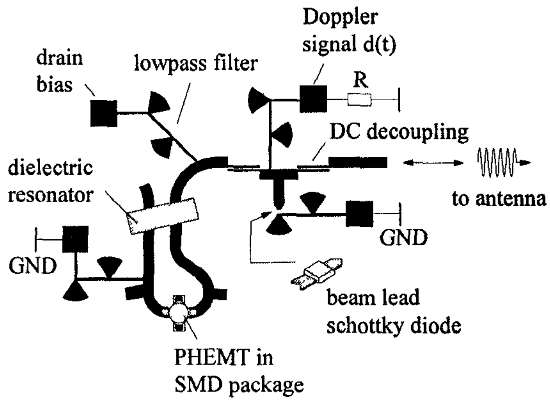

Fig. 1: 24 GHz oscillator / detector module with fundamental-frequency transmission-type DRO and schottky diode detector.

QUASI-HETERODYNE QUADRATURE RECEIVER

The sensitivity of Doppler sensors with a homodyne receiver is considerably affected by the low-frequency noise of the microwave transistor used in the oscillator. Microwave transistors exhibit a so called flicker noise, which has a noise power density characterized by an 1/f-function. In MESFETs and HEMTs, flicker noise is the main low-frequency noise source up to a typical corner frequency in the MHz region. Due to transistor nonlinearities, the flicker noise is upconverted to near-carrier phase- and amplitude noise sidebands of the oscillator frequency spectrum [4]. The phase noise of the oscillator is irrelevant in short-range sensor applications, whereas its 1/f amplitude fluctuations significantly reduce the signal-to-noise ratio, i.e. the sensitivity of conventional Doppler radar sensors.
The novel sensor concept shown in fig. 2 is an extension of the CW oscillator / detector module (fig. 1). An additional microwave phase shifter has been inserted into the transmit / receive branch of the Doppler sensor between

the schottky diode detector and the sensor antenna. This gives the opportunity to a phase shift keying of the radar signal, which is done by using a periodic modulation signal m(t) with a frequency f_m much higher than the maximum Doppler signal frequency (e.g. f_m = 1 MHz). The demodulation of the PSK Doppler signal d(t) is achieved with a SPDT switch, such that two phase shifted Doppler signals $d_1(t)$ and $d_2(t)$ are obtained.

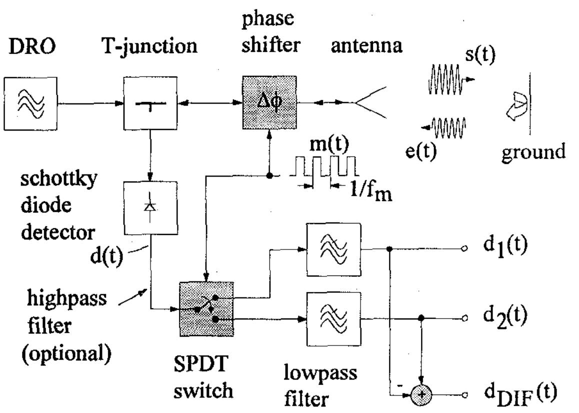

Fig. 2: Schematic of a PSK Doppler sensor.

Using a phase shift of $|2\cdot\Delta\phi|$ = 90°, $d_1(t)$ and $d_2(t)$ are representing the orthogonal I and Q components of a complex Doppler signal vector $\underline{d}(t) = d_1(t) + jd_2(t)$. In this case, the function of a quadrature receiver is realized, which allows to detect the direction of vehicular motion.

Additionally, a noise reduction capability is attained: Both Doppler signals $d_1(t)$ and $d_2(t)$ contain fully correlated noise distortions caused by the amplitude fluctuations of the DRO (1/f-noise). Consequently, the difference term $d_{DIF}(t) = d_2(t) - d_1(t)$ is a noise-reduced Doppler signal with a much higher signal-to-noise ratio. From another point of view, the phase shift keying leads to an upconversion of the Doppler signal into sidebands of the microwave carrier at integral multiples of the modulation frequency f_m, whereas the oscillator noise remains in the baseband. Therefore, a highpass filter arranged between the schottky diode detector and the SPDT switch will stop the 1/f-noise and pass the Doppler signal, such that a quasi-heterodyne reception is established.

The main component of the PSK Doppler sensor is the 24 GHz phase shifter shown in fig. 3. The microstrip circuit is based on a hybrid-coupled reflection-type phase shifter structure [5]. The use of a ratrace hybrid instead of a branchline coupler allows a very broadband operation. To obtain a phase of the scattering parameter S21 (S12) alternating between two states with a phase shift of $\Delta\phi$, the modulation signal m(t) biases the two PIN diodes periodically in forward and reverse direction.

The measured phase vs. frequency characteristic of the phase shifter is depicted in fig. 4. Within a frequency band of about 2 GHz the unidirectional phase varies less than ± 2° at a phase shift of $\Delta\phi$ = 135°. Therefore, the Doppler signals $d_1(t)$ and $d_2(t)$ will be precisely orthogonal. The insertion loss of the phase shifter is about 1 dB and the amplitude symmetry deviation of the two phase states is less than 1 dB.

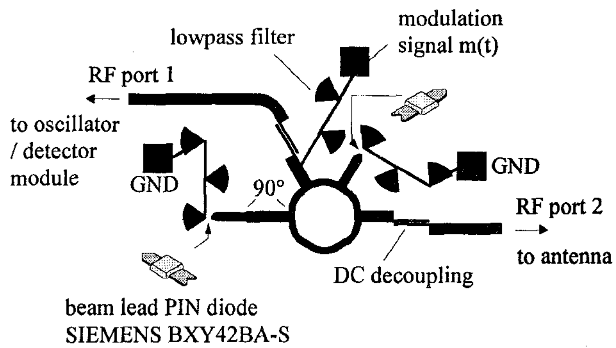

Fig. 3: 24 GHz transmission-type PIN-diode phase shifter.

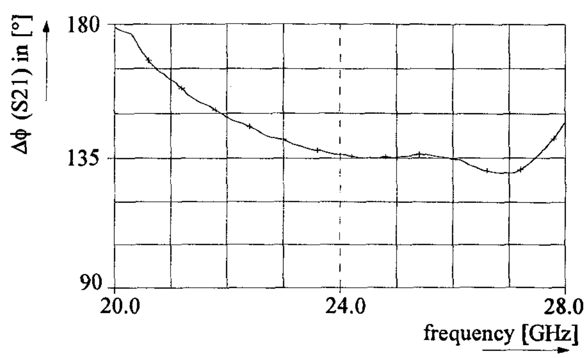

Fig. 4: Measured transmission phase shift.

ENHANCEMENT OF THE SENSOR SENSITIVITY

The noise reduction effect has been verified by a comparison of the Doppler signal noise floor obtained from a homodyne receiver and the new type of quasi-heterodyne receiver. Both noise spectra have been measured with a receiver bandwidth of 3.5 kHz. The noise spectrum at the schottky diode detector output, shown in fig. 5, exhibits the typical 1/f-noise characteristic regarding to the amplitude fluctuations of the DRO. This homodyne reception results in a reduced sensitivity at low frequencies and is one of the main reasons for the limitation in measurement accuracy of conventional Doppler sensors operating at very low speeds.

This limitation in sensor sensitivity no longer holds for the quasi-heterodyne receiver. Fig. 6 demonstrates the significant 1/f-noise suppression attained with the new concept. Now, the theoretical upper limit in sensor sensitivity, which is given by the white noise power contained within the receiver bandwidth, is achieved.

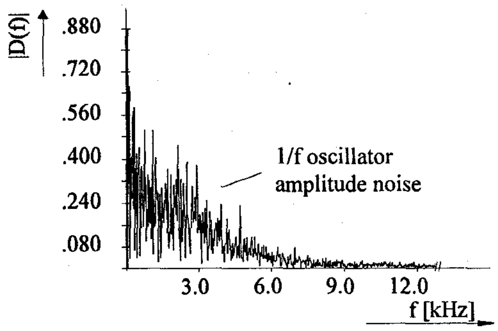

Fig. 5: Typical noise floor of the Doppler signal due to the 1/f-noise of the oscillator (homodyne receiver).

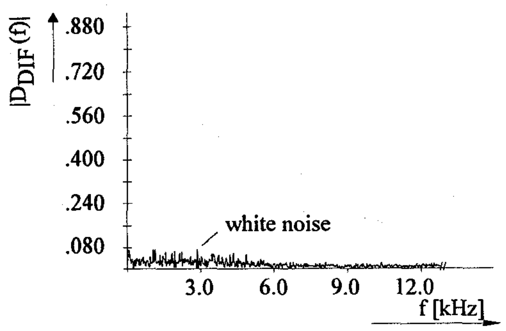

Fig. 6: White noise floor of the quasi-heterodyne receiver. (oscillator 1/f-noise has been suppressed.)

RANGE SELECTIVITY

The detection area of a conventional CW Doppler sensor is determined by the radiation pattern of the sensor antenna. The spot on the road illuminated by the main antenna beam is called the antenna footprint. In practice, the angular selectivity of the antenna is not sufficient. Spurious Doppler signals, e.g. coherent road reflections as indicated in fig. 7, are received due to the antenna sidelobes [6]. Furthermore, the signal is distorted by multipath transmission emerging from strong reflections of the road, moving parts of the own vehicle (vibrating objects, rotating wheels) or adjacent other vehicles.
The new idea of a coded Doppler radar sensor aims at the establishment of a range selectivity of the sensor [7]. This range selectivity is equivalent to the capability of the Doppler sensor to focus the Doppler signal evaluation to the antenna footprint, whereas spurious Doppler signals from outside the defined measurement range ΔR are inherently suppressed.

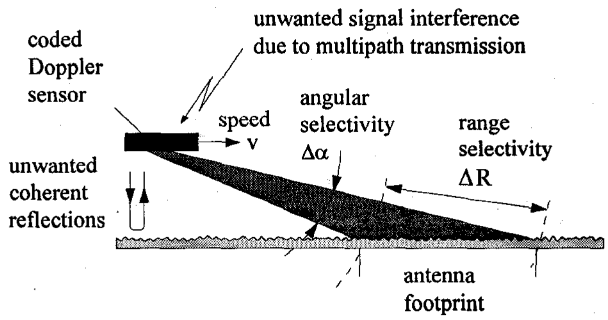

Fig. 7: Vehicle ground-speed measurement using a coded Doppler radar sensor.

The range selectivity is accomplished by a spread-spectrum bipolar phase shift keying (BPSK) of the radar signal [8]. Digitally encoding the phase of the 24 GHz microwave signal in a pseudo-random manner, i.e. using a pseudo-noise (PN) sequence, creates a quasi-stochastic phase jitter imposed on the radar signal. This results in a deliberate reduction of the coherence length of the radar signal and leads to a range selectivity. The schematic of a pseudo-noise coded Doppler radar sensor is shown in fig. 8.

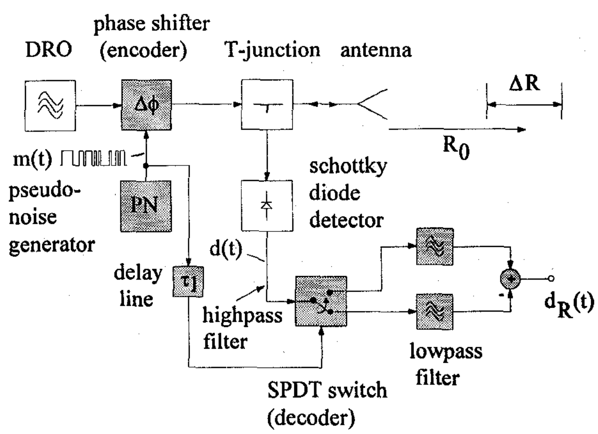

Fig. 8: Schematic of a pseudo-noise coded Doppler sensor.

The modulation port of the phase shifter used to encode the microwave signal is fed by a pseudo-noise generator. A crosscorrelation of the received encoded Doppler signal and the reference code is achieved with a SPDT switch used as a decoder. The measurement distance R_0 is determined by a coaxial delay line ($R_0 = c \cdot \tau_1 / 2$), whereas the width of the measurement range ΔR can be controlled by the bitrate of the PN signal ($\Delta R = c / f_{bit}$).

The range selectivity of the PN coded Doppler sensor has been verified by measuring the amplitude of the Doppler signal $d_R(t)$, which has been generated using a sliding short in a waveguide of 1.8 meters length, as a function of the distance R. The measured curve (fig. 9) is equivalent to the autocorrelation function of the pseudo-noise signal. Using a 255 bit PN signal with a bitrate of f_{bit} = 80 MHz, a 20 dB width of the measurement range of approximately ΔR = 3.0 m is obtained.

This demonstrates the capability of a coded Doppler sensor to confine the distance range from which Doppler signals are evaluated to the antenna footprint. Using this technique, a very high sensitivity is achieved within the intended detection area, combined with a high suppression of spurious Doppler signals from outside of this region.

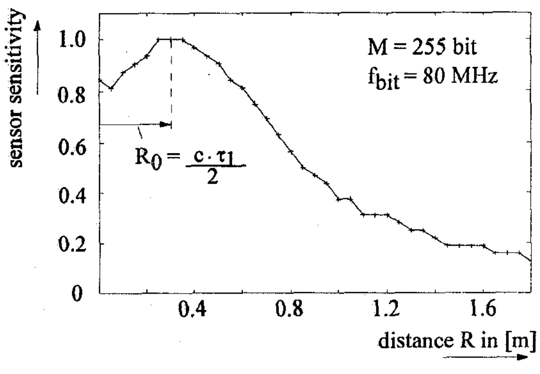

Fig. 9: Measured sensitivity of the pseudo-noise coded Doppler sensor as a function of the distance.

CODED 24 GHZ RADAR FRONT-END

Fig. 10 depicts the coded 24 GHz radar front-end built in low-cost hybrid microstrip technology. The compact-sized sensor has the dimensions 60 x 80 x 25 mm. First prototype versions of the sensor proved to operate reliably and provided good measurement results [9].

CONCLUSION

A new 24 GHz Doppler sensor system for high precision vehicle position and ground-speed sensing has been reported. The investigated spread-spectrum coding provides a very high sensor sensitivity as well as the unique capability to focus the measurement to a given measurement distance (range selectivity).

These substantial technical improvements are achieved without the use of costly components, which is essential in future high-volume automotive applications.

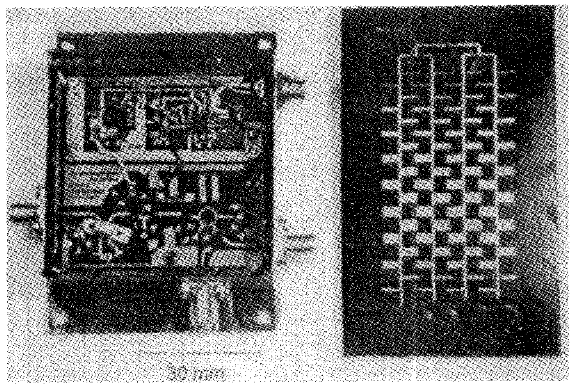

Fig. 10: 24 GHz coded radar front-end comprising of a fundamental-frequency DRO, a schottky diode detector, a PSK modulator and a travelling-wave patch antenna.

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