Small-aperture, high-resolution beam-scanning antenna array using nonlinear signal processing

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Abstract — **A high-resolution two-element antenna array is demonstrated using nonlinear signal processing of the output signals of the two antennas. The basic principle of this method is to convert the output signal of each antenna into a train of very short pulses and to extract a time delay between the two pulse trains by correlation. Compared to previous work, the input signals in this work are first downconverted to a low IF frequency, and then a nonlinear signal processing can be achieved using fast digital ICs. An experimental receiver was built, and the general principle of the new approach is demonstrated. In addition, including digital delay ICs into each channel, even beam scanning is included. Adding a transmitter with a FM-modulation, a simple radar sensor was built up.**

I. Introduction

It is well known that the beamwidth of an antenna is depending on the operating frequency of the antenna and its aperture in the respective plane. Scanning the beam of such an antenna, a resolution between waves of different angles of incidence is possible if these angles of incidence differ by at least the antenna beamwidth. If there is, however, only one incident wave, its angle of incidence can be detected with higher accuracy by evaluating the phase difference of the signals of two antennas, even if these are closely spaced. A well known technique, for example, uses a monopulse antenna arrangement where small phase differences between two antennas are extracted by comparing constructive and destructive superposition of the two signals.

An interesting alternative approach was proposed recently using a nonlinear signal processing [1]. The sinusoidal input signal of two antennas is converted into a train of short pulses which are fed into a correlator. An output signal only occurs if the pulses overlap. The accuracy is the better the shorter the pulses are. With a high frequency, however, generating very short pulses gets more and more difficult.

This paper investigates the method as described above, however after a frequency downconversion to a lower IF frequency. With this downconversion, the *phase difference* between the two channels is preserved – but at the lower IF frequency. This is associated with a *virtual increase in signal delay* between the two signals according to the ratio of RF and IF frequency. Furthermore, at frequencies low enough, digital techniques can be applied to generate very short pulses (compared to the IF period length), and digital delay ICs can be used to even scan the resulting "antenna beam". In the following, an experimental antenna and signal processing setup is described which greatly improves the angle resolution of an array of two antennas spaced at three quarters of a wavelength. "Beam scanning" up to ±40° could be achieved. Furthermore, an FM-modulated transmitter is added to this receiver, resulting in a simple small sensor.

II. Circuit Concept and Realization

For this investigation, an RF frequency of 2.45 GHz was selected as many ICs were easily available. The general principle, however, can equally be applied to much higher frequencies, too, even in the millimeter-wave frequency range. A 10 MHz IF frequency was selected, so off-the-shelf digital components could be used for the signal processing. A general block diagram of the antenna and receiver arrangement as described in this contribution is given in Fig. 1. The setup consists of two microstrip patch antennas with a distance of ¾ λ. An RF amplifier, a frequency downconverter, and an IF amplifier are connected to each antenna element.

In the digital part of the receiver, each IF signal is further amplified by limiting amplifiers; a comparator converts the sinusoidal signals to rectangular ones. A delay circuit is added to the rectangular signals in both channels. Finally, a pulse former converts the signals to short pulses (down to 5 ns length). These short pulses of both channels are combined in an AND gate; the output is low-pass filtered and amplified. Considering the AND gate as a multiplier for the digital signals, and the low-pass filter as an integrator, an autocorrelation function results at the system output varying the signal delay, either by varying one of the signal delay times in the digital part of the receiver or by varying the angle of incidence of the received wave. This can be simulated by simply rotating the antenna array which, on the other hand, is equivalent to measuring an antenna diagram.

While, for example, a beam angle of 45° away from broadside results in a delay of about 0.22 ns between the signals received by the two antennas at 2.45 GHz, this is increased to a delay of 53 ns at 10 MHz. With the short pulses generated as described before, this delay is detected with high accuracy.

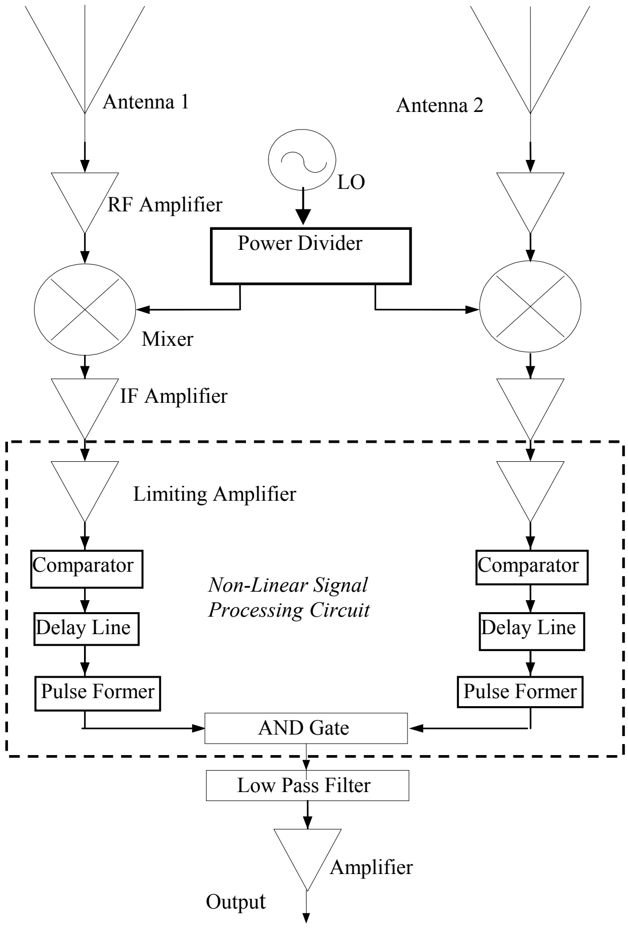

Fig. 1: Block diagram of the receiver circuit

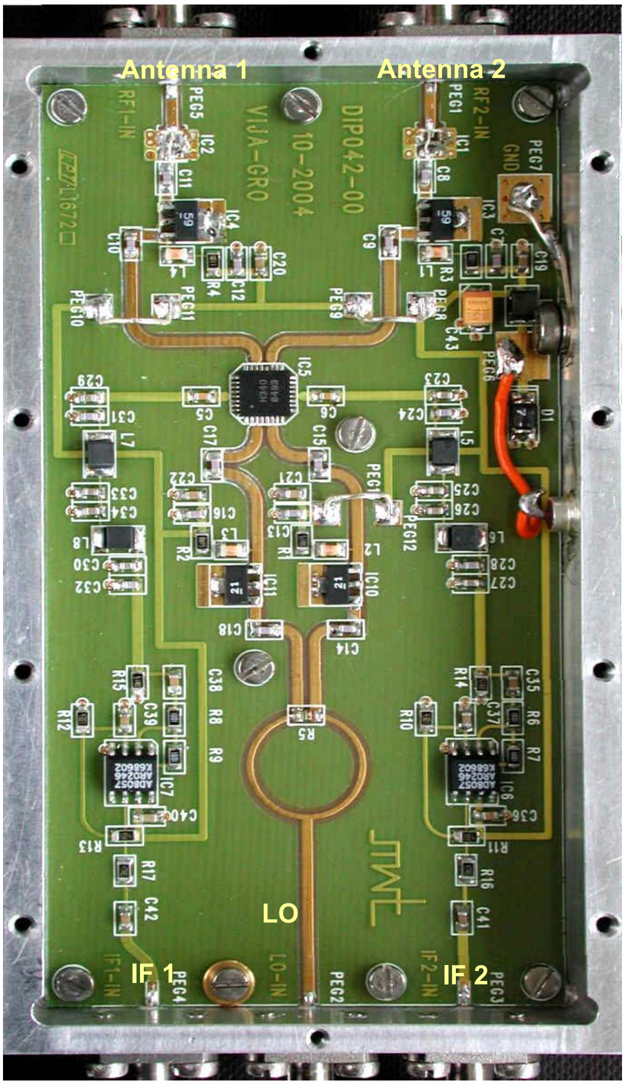

Fig. 2: Photograph of the analogue receiver circuit

III. Results of Angle Measurements

The planar antennas (see inset in Fig. 3) and the receiver/signal processing circuit as shown in Fig. 1 were built up using commercially available devices and ICs. The analogue circuit board is shown in the photograph of Fig. 2.

As a first test, the analogue signals of the two antennas were directly combined in phase, and the resulting H-plane antenna diagram was measured (Fig. 3), resulting in a beamwidth of 40° (this later on can be used as a reference antenna diagram). Following this, the complete receiver arrangement was placed on the turntable in the antenna test chamber, and the output voltage was recorded as a function of angle for different adjustments of the delay in one of the channels (Fig. 4). Triangular responses can be observed according to the autocorrelation function of the nearly rectangular pulses generated from each antenna signal. In the center (around 0°, no delays adjusted in both channels), the signal width at zero voltage is about 8°, and at a normalized value of 0.7, the widths are slightly below 3°. If delay is added to one of the channel, an equivalent delay between the signals of a plane wave received by the two antennas is compensated. Consequently, the maximum signal is received at the respective angle of the incident wave, or in other words, the antenna diagram is scanned. Fig. 4 shows the resulting "angular responses for different values of delay. Scanning angles of about 5°, 10°, 20°, and 40° are demonstrated in this figure. Adjusting delay in the other channel "scans" the antenna diagram to the other side. (Due to some symmetry problems in the digital circuits of one of the channels, some adjustments lead to a slight deterioration for scanning to one side.)

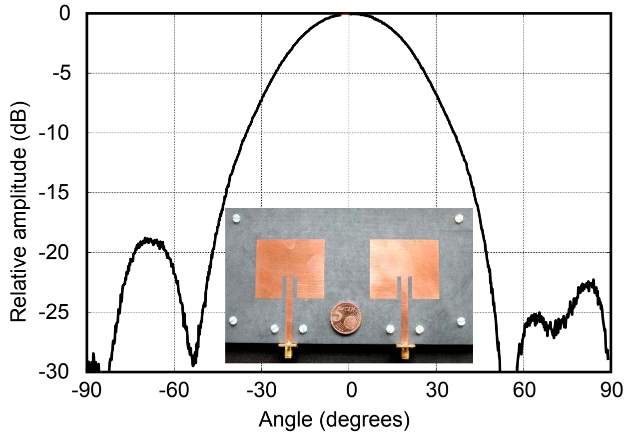

Fig. 3: H-plane radiation diagram of the array of two microstrip patches (combined in-phase).

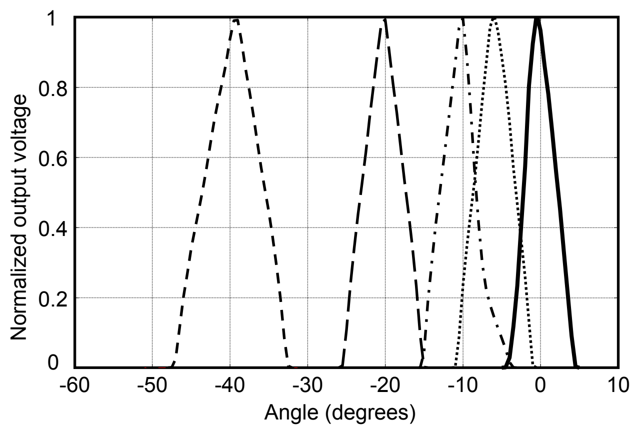

Fig. 4: H-plane angular resonses of the complete system (Fig. 1) for different delays adjusted in one of the channels.

IV. Small Radar Sensor

In a next step, the receiver was combined with a FM-modulated transmitter; a separate antenna is used for transmitting. To achieve a sufficient range resolution, a frequency deviation of the modulation ramp of about 200 MHz is used. This, however, is neither compatible with the receiver IF frequency nor the IF bandwidth. Therefore, a modified arrangement according to the block diagram in Fig. 5 is used. Both the transmit oscillator and the LO are modulated with a ramp, and a PLL circuit, together with a 10 MHz crystal oscillator, provides a constant IF frequency of 10 MHz. The two signals from the receive antennas are fed to the nonlinear signal processing. The IF signal of one channel (or a combination of both channels) is downconverted to the baseband, using the 10 MHz reference as LO signal. In this way, a constant low frequency IF signal with low bandwidth is maintained for the nonlinear signal processing, and the first IF avoids the problems of 1/f-noise and oscillator sideband noise associated with many FM/CW sensors using direct downconversion into the baseband. The linear output signal contains the range information; it is amplified again, A/D converted, and undergoes a fast Fourier transform, from which the target distance can be determined.

In contrast to the nonlinear signal processing, the ranges of multiple targets can be determined in this way; the respective angle information, however, can be extracted with this setup if there is a single target only. Thus, this sensor may be used to control a single vehicle or person in a limited range, e.g. for possible security applications. First experiments indicate that the principle of nonlinear angle detection can be applied to two or more targets at *different* distances if the nonlinear operations are performed *after* the range determination.

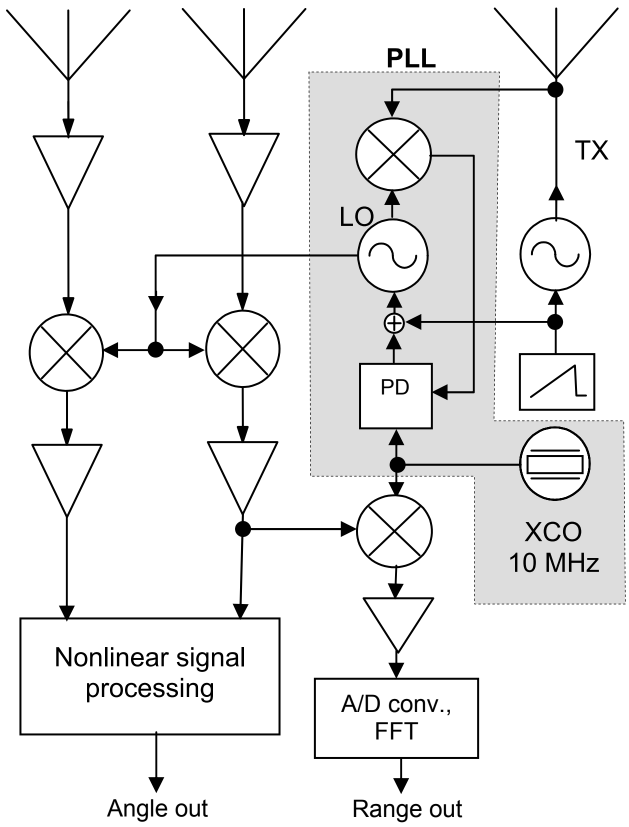

Fig. 5: Block diagram of the radar sensor. (TX: transmitter, PLL: phase lock loop, PD: phase detector, XCO: crystal oscillator, FFT: fast Fourier transform)

A first test of the sensor was performed using a cable to connect transmitter and receiver, thus avoiding any interference. The Fourier transforms of two measurements with cables of about 15 m and 120 m electrical length, respectively, are plotted in Fig. 6. According to the two-way evaluation of the radar signals, peaks occur at 7.5 m and 60 m. Following this, measurements were performed near to our lab. The measurement setup with the sensor is displayed in Fig. 7. As the elevation diagrams of the employed patch antennas are quite broad, some difficulties occurred due to close range reflections from the grassy ground. In addition, the first setup did not include a sensitivity frequency control to attenuate close-range signals. Nevertheless, a 1 m^2 target (corner reflector) could be clearly detected and separated from bushes in the background (Fig. 8). According to the missing range filtering, close-by reflections and direct coupling between the antennas show strong amplitudes; this however can be improved adding high-pass filtering to the IF to compensate for the $1/f^4$ dependence of the receive signal.

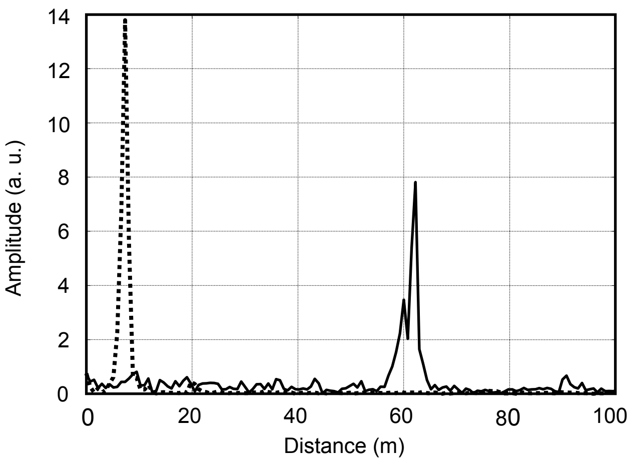

Fig. 6: FFT of the test measurements of two cables of 15 m and 110 m electrical lengths. (Ramp 10 ms, sampling rate 400 kHz, 4096 points for FFT).

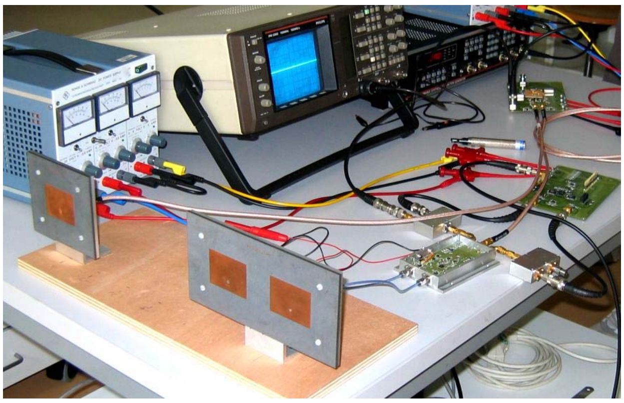

Fig. 7: Photograph of the test setup of the radar sensor.

V. CONCLUSION

An experimental receiver setup was built and tested for high resolution detection of the angle of arrival of an incoming wave using downconversion and simple nonlinear/digital signal processing. With two patch antennas spaced at three quarters of a wavelength, the resulting angle accuracy was about 3° compared to 40° of the array beamwidth without the nonlinear processing. The "beam direction" of the receiver can be scanned over ±40° using digital delay ICs. Although this arrangement works only for a single incident wave, applications could be the tracking of vehicles or persons carrying a transmitter; several target could be distinguished using different frequencies which are filtered and processed separately in the receiver. The principle has been demonstrated at a frequency of 2.45 GHz, but I will work for higher frequencies equally. A first step has already been done to extend this principle to a close-range radar sensor using FMCW principles. Transmitter and LO are joined together by a PLL circuit maintaining an IF frequency of 10 MHz, and the range signal is processed using a second downconversion into the baseband. The IF frequency is extracted from one or both channels (before the nonlinear processing is done), and the distance is evaluated independently from the nonlinear signal processing. First results for range detection have been demonstrated. In a next step, both nonlinear signal processing for angle detection and range detection have to be operated together.

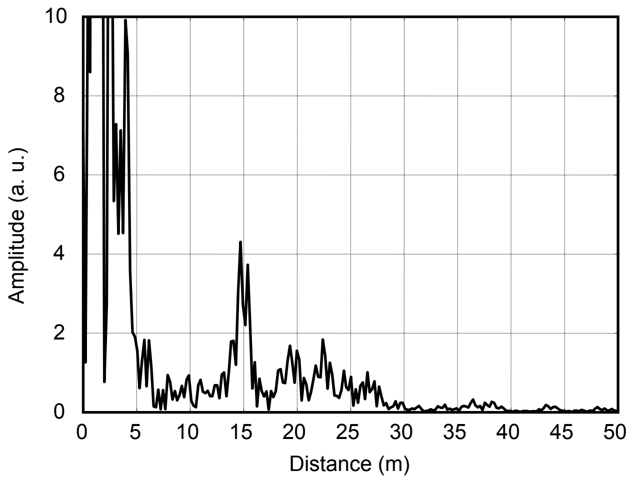

Fig. 8: FFT of a reflector of 1 m^2 radar cross section at a distance of 15 m. (Ramp 2 ms, sampling rate 600 kHz, 4096 points for FFT).

REFERENCES

[1] Zoya Popovic, Christi Walsh, Paul Matyas, Charles Dietlein, Dana Anderson: High-Resolution Small-Aperture Angel of Arrival Detection Using Nonlinear Analog Processing. IEEE Int. Microwave Symp. 2004, Fort Worth, pp. 1749 – 1752.