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ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 42-1

“FMCW Radar”
(«РЛС с непрерывным ЧМ излучением»)

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"FMCW Radar"

(«РЛС с непрерывным частотно-модулированным излучением»)

Журнальные публикации

"Wireless SAW Temperature Sensor System for High-Speed High-Voltage Motors"

This paper gives an overview on the system development of a wireless surface acoustic wave (SAW) temperature measurement application in high-speed high-voltage motors. The measurement location of interest is on the rotor in the vicinity of the copper squirrel cage. To fit the sensor in a 4 mm bore, a custom packaging with outer dimensions of 10.0 Ч 3.1 Ч 2.0 mm3has been developed. For the purpose of interrogation a mechanically robust metal slot antenna has been designed to withstand rotation speeds up to 15 000 rpm. As the sensor interacts only during a very short time of a few 100 µs with the reader antenna a fast frequency modulated continuous wave (FMCW) reader was developed. The reader operates in the ISM band of 2.4 GHz and achieves a typical sweep time for data acquisition of 100 µs. The sensor system has been tested both in test bed and real engine conditions and performed stable read outs, although in the real engine signal behavior is disturbed by reflections and possibly electromagnetic field bursts caused by the power converter. [J1]

"A Transceiver Module for FMCW Radar Sensors Using 94-GHz Dot-Type Schottky Diode Mixer"

In this study, we fabricated a 94-GHz transceiver module for a millimeter-wave (MMW) frequency modulation continuous wave (FMCW) radar sensor. The transceiver modules consist of a waveguide voltage-controlled oscillator (VCO) and Rx module using a single balanced mixer. We designed a mixer with a conversion loss of 6.4 dB, without using an amplifier. Also, the waveguide VCO consisted of an InP Gunn diode, a varactor diode, two bias posts with LPF, and a Magic Tee for the MMW radar transceiver. The fabricated VCO has a tuning range of 1280 MHz by a varactor bias of 0~20 V, 1.69% linearity range of 680 MHz, and current consumption of 154 to 157 mA. The completed module has a good conversion loss of 10.6 dB with an LO power of 11.4 dBm at 94 GHz. With this RF and LO input power, the conversion loss was maintained between 10.2-11.5 dB in the RF frequency range of 93.67-94.95 GHz. [J2]

"Signal Modeling and Analysis of a Planar Phased-Array FMCW Radar With Antenna Switching"

A frequency-modulated continuous-wave (FMCW) radar system with a planar phased array based on antenna switching is considered. The radar system consists of N_{1}linear antenna arrays where each linear antenna array consists of N_{2}receiving antennas. In each cycle, the receiving antennas on each linear antenna array are switched to the single receiving channel in turn from the first antenna to the N_{2}th antenna. An accurate and detailed system model for the radar system is addressed. The Cramйr-Rao lower bound (CRLB) analysis on the accuracy of estimating the azimuth angle, elevation angle, velocity, and range using the radar system is presented. [J3]

"A 77 GHz 90 nm CMOS Transceiver for FMCW Radar Applications"

The first 77 GHz frequency modulated continuous wave (FMCW) radar transceiver IC with an accurate FMCW chirp signal generator using a 90 nm CMOS process is presented. To realize accurate FMCW radar system in CMOS, a PLL synthesizer based FMCW generator with chirp smoothing technique that is able to output linear FMCW frequency chirp using a nonlinear reference chirp signal supplied from a low spec/cost digital-oriented frequency reference is applied. The fabricated IC consists of an LNA, a down-conversion mixer with an output buffer, a driver amplifier, a power amplifier with power combiner, an LO distributer and an FMCW synthesizer. The measured FMCW signal from the proposed FMCW generator achieves 93 kHz frequency error (nonlinearity) at the 77 GHz chip signal. Radar performance of the IC has less than 1% ranging error from 1 m to 8 m distance from the measurement in a laboratory. These results show the transceiver achieves a fundamental function for radar applications with 520 mW power consumptions. [J4]

"Predicting Millimeter Wave Radar Spectra for Autonomous Navigation"

Millimeter Wave (MMW) radars are currently used as range measuring devices in applications such as automotive driving aids (Langer and Jochem, 1996), (Rohling and Mende, 1996), the mapping of mines (Brooker

et al., 2005) and autonomous field robotics (Brooker, 2001), (Langer, 1996). This recent interest is largely due to the advantages MMW radars offer over other range measuring sensors, as their performance is less affected by dust, fog, rain or snow and ambient lighting conditions. MMW radars can provide received signal strength values, at all discrete range intervals, within the working range of the radar (Clark and Durrant-Whyte, 1997), (Scheding et al., 2002). The received power versus range spectra hence contain useful range to target information, but are also corrupted by noise. User defined stochastic algorithms can then be implemented, which exploit this rich data to improve object detection and mapping performance. This is in contrast to many other range measuring devices which typically internally threshold received signals, to provide single hard decisions only, on the estimated range to objects (Mullane, 2007). This paper addresses the issues of predicting the power-range spectra from MMW radars which use the Frequency Modulated Continuous Wave (FMCW) range estimation technique. This is important for two reasons. First, in automotive and autonomous robotic applications, such sensors are used in conjunction with vehicle navigation and map state estimation filters. This is so that (typically uncertain) vehicle motion knowledge can be optimally fused with the noisy sensor information, to infer estimates of the state of interest (typically, the vehicle's pose (position and orientation) and/or information of the surrounding object locations). Hence, it is essential that predicted power versus range spectra can be computed, to apply a Bayesian recursive estimation framework, based on previous measurements, and uncertain vehicle motion information. Second, it- is extremely useful to be able to simulate MMW radar data, given certain environmental configurations. This aids the development of reliable object detection algorithms, based on theoretical sensor and noise models, which can then be applied more effectively to real MMW radar data. [J5]

"Design and Performance of a 24-GHz Switch-Antenna Array FMCW Radar System for Automotive Applications"

We develop a 24-GHz switch-antenna array frequency-modulated continuous-wave (FMCW) radar system composed of a single transmitter, a single transmitting antenna, four receiving antennas, a single-pole four-throw (SP4T) switch, and a single receiving channel. The antennas are integrated with radio-frequency (RF) and intermediate-frequency (IF) circuits to reduce the interconnection loss and realize a compact whole size. The receiving antennas are periodically switched to the single receiving channel. The performance of the developed system is evaluated using beamforming methods to estimate the angle, range, and velocity. [J6]

"Focus FMCW SAR Data Using the Wavenumber Domain Algorithm"

The combination of frequency-modulation continuous-wave (FMCW) technology and synthetic aperture radar (SAR) promises a lightweight, cost-effective, and high-quality imaging sensor for remote sensing. However, the long signal duration time leads to the failure of the conventional start/stop approximation of the pulsed SAR. In this paper, a signal model is proposed to address the effects of the continuous motion during the transmit time on the echoed signal. Based on the model, an analytical point target reference spectrum is derived. From the spectrum, it will be seen that the continuous motion introduces an additional range-azimuth coupling term and a range walk term compared with the conventional pulsed SAR. The range walk term is well known, whereas the foregoing range-azimuth coupling term is formulated for the first time in the FMCW SAR community. For the squint and spotlight modes, these range walk and range-azimuth coupling terms might significantly degrade the image quality. In this paper, based on the proposed analytical signal model, we further discuss the application of the wavenumber domain algorithm for the FMCW SAR data. In addition, different approximations of the Stolt mapping are made to highlight the effect of the range-dependent higher-order range-azimuth coupling terms on the 2-D impulse responses. Finally, X-band simulated experiments and Ka-band real FMCW SAR data are used to validate the signal model and the processing method. [J7]

"Integrated Active Pulsed Reflector for an Indoor Local Positioning System"

This paper presents an indoor localization system based on a frequency modulated continuous wave radar in the industrial-scientific-medical band at 5.8 GHz. An integrated active pulsed reflector behaves as a backscatter by regenerating the incoming phase with phase coherent startup at a constant frequency. The base station (BS) determines the distance to this reflector with a round-trip time-of-flight measurement. The active pulsed reflector is built around a switchable and tunable oscillator. The circuit has been fully integrated in a 0.18-??m CMOS technology. Outdoor measurements revealed a positioning accuracy of 15 cm, while in a harsh multipath environment with omnidirectional antennas a positioning accuracy of 32.88 cm was measured. The localization system is capable of detecting multiple reflectors at the same time, and no synchronization between BSs is needed. [J8]

"A new method for blood velocity measurements using ultrasound FMCW signals"

The low peak power of frequency-modulated continuous wave (FMCW) radar makes it attractive for various

applications, including vehicle collision warning systems and airborne radio altimeters. This paper describes a new ultrasound Doppler measurement system that measures blood flow velocity based on principles similar to those of FMCW radar. We propose a sinusoidal wave for FM modulation and introduce a new demodulation technique for obtaining Doppler information with high SNR and range resolution. Doppler signals are demodulated with a reference FMCW signal to adjust delay times so that they are equal to propagation times between the transmitter and the receiver. Analytical results suggest that Doppler signals can be obtained from a selected position, as with a sample volume in pulse wave Doppler systems, and that the resulting SNR is nearly identical to that obtained with continuous wave (CW) Doppler systems. Additionally, clutter power is less than that of CW Doppler systems. The analytical results were verified by experiments involving electronic circuits and Doppler ultrasound phantoms. [J9]

"SAR Imaging with Noise Radar"

Two ground-based coherent imaging systems designed on the basis of noise radar technology (NRT) using continuous waveform with a linear synthetic aperture and pulse coherent noise waveform with a circular synthetic aperture are presented. A short description of noise waveform synthetic aperture radar (SAR) theory and data processing algorithms are given. Experimental results obtained show that the quality of the imagery is comparable to that of frequency-modulation continuous-wave (FMCW) or stepped frequency radar systems. Experimental validation of the technique at different locations provides confidence in the ability of noise waveform SAR to achieve high-resolution imaging at low cost. The exploitation of the interferometric phase combining pairs of images spaced in time is shown to allow the detection of displacements in the scene with a submillimeter accuracy. [J10]

"A Fully-Integrated 77-GHz FMCW Radar Transceiver in 65-nm CMOS Technology"

A fully-integrated FMCW radar system for automotive applications operating at 77 GHz has been proposed. Utilizing a fractional- synthesizer as the FMCW generator, the transmitter linearly modulates the carrier frequency across a range of 700 MHz. The receiver together with an external baseband processor detects the distance and relative speed by conducting an FFT-based algorithm. Millimeter-wave PA and LNA are incorporated on chip, providing sufficient gain, bandwidth, and sensitivity. Fabricated in 65-nm CMOS technology, this prototype provides a maximum detectable distance of 106 meters for a mid-size car while consuming 243 mW from a 1.2-V supply. [J11]

"DC-Offset Compensation Concept for Monostatic FMCW Radar Transceivers"

A novel dc-offset compensation technique for monostatic frequency-modulated continuous-wave (FMCW) transceivers is presented. This approach uses the intermediate frequency (IF) port of the active direct-conversion mixer to access its collector resistors. Additional external variable resistors in parallel connection can vary the total load resistance in each branch and hence compensate or generate a dc-offset voltage at the output. Since the wiring is located on the low-frequency side of the mixer, the variable resistors can also be external (off-chip), which offers great flexibility and eases application. The concept was successfully tested with an integrated 77 GHz automotive radar mixer fabricated in a 200 GHz fTSilicon Germanium (SiGe) bipolar technology. [J12]

"HFSW Radar Model: Simulation and Measurement"

High-frequency surface-wave (HFSW) radars are usually used to remotely measure oceanographic parameters. These systems can also potentially detect targets beyond the conventional microwave radar coverage. In this paper, the backscattered Doppler spectrum made up of the sea clutter, ship echoes, and the background noise has been modeled. Taking into account the propagation and the signal-processing effects, a range-Doppler image has been generated. This model can be used for different purposes like the (theoretical) evaluation of detection performance. This paper gives an overview of the theoretical elements for modeling the backscatter signal. The processing effects on the range-Doppler image and the time-evolving target signature are also introduced. Some of the simulated elements and the obtained range-Doppler images are compared with real data. Finally, from this model, the detection capabilities of HFSW radars are evaluated. [J13]

"A Through-Dielectric Radar Imaging System"

Through-lossy-slab radar imaging will be shown at stand-off ranges using a low-power, ultrawideband (UWB), frequency modulated continuous wave (FMCW) radar system. FMCW is desirable for through-slab applications because of the signal gain resulting from pulse compression of long transmit pulses (1.926-4.069 GHz chirp in 10 ms). The difficulty in utilizing FMCW radar for this application is that the air-slab boundary dominates the scattered return from the target scene and limits the upper bound of the receiver dynamic range, reducing sensitivity for targets behind the slab. A method of range-gating out the air-slab boundary by significant band-

limiting of the IF stages facilitates imaging of low radar cross section (RCS) targets behind the slab. This sensor is combined with a 1D linear rail and utilized as a rail synthetic aperture radar (SAR) imaging system. A 2D model of a slab and cylinder shows that image blurring due to the slab is negligible when the SAR is located at a stand-off range of 6 m or greater, and thus, the two-way attenuation due to wave propagation through the slab is the greatest challenge at stand-off ranges when the air-slab boundary is range-gated out of the scattered return. Measurements agree with the model, and also show that this radar is capable of imaging target scenes of cylinders and rods 15.24 cm in height and 0.95 cm in diameter behind a 10 cm thick lossy dielectric slab. Further, this system is capable of imaging free-space target scenes with transmit power as low as 5 pW, providing capability for RCS measurement. [J14]

"Waveform-Diversity-Based Millimeter-Wave UAV SAR Remote Sensing"

To integrate a synthetic aperture radar (SAR) into an operational unmanned airborne vehicle (UAV), it should be as small as possible to meet stringent limitations of size, weight, and power consumption. It appears that the novel combination of millimeter-wave frequency-modulated continuous-wave (FMCW) technology and SAR techniques can provide an optimal solution. However, some efficient techniques should be applied to resolve range/Doppler ambiguities in FMCW UAV SAR systems. As such, a technique of waveform-diversity-based millimeter-wave UAV SAR imaging is presented in this paper. Along with the described system concept and signal model, the performance of the diversified waveforms evaluated by their cross correlations is detailed. As the conventional stop-and-go approximation is not valid for FMCW SAR, a modified wavenumber-domain algorithm with a consideration of continuous antenna motion during transmission and reception is derived. This imaging algorithm is validated with computer simulations. Furthermore, one parallel direct-digital-synthesizer-driven phase-locked-loop synthesizer with adaptive nonlinearity compensation, which has been validated by the experimental results, is proposed to obtain a millimeter-wave FMCW signal with fine frequency linearity. [J15]

"In-band interference reduction in FMCW channel data using Prony modelling"

He is shown that Prony modelling can be used to reduce the effect of in-band interference in frequency modulated continuous-wave (FMCW) channel data. Results of the modelling are examined by comparing average power delay profiles and Doppler spectra with those obtained from FFT processing. [J16]

"Design of -Band RF CMOS Transceiver for FMCW Monopulse Radar"

In this paper, an X-band CMOS single chip integrating 16 building blocks is developed for frequency modulation continuous wave radar application. The quadrature and monopulse transceiver consists of a voltage-controlled oscillator, amplifiers, Wilkinson power dividers, 90deg hybrid low-noise amplifiers, rat-race hybrid, a single-pole double-throw switch, an active bandpass filter (BPF), and mixers. The transceiver is fabricated in a standard mixed-signal/RF bulk 0.18-mum CMOS technology with a chip area of 2.6 mm 3.3 mm, including contact pads. The transceiver is implemented by meandered complementary-conducting-strip transmission lines demonstrating their capability of miniaturizing circuits such as 90deg hybrid and rat-race hybrid with 95% and 98% size reduction compared to the prototype designs, respectively. The active BPF consumes 4.5 mW achieving 0-dB insertion loss at the passband. The total power consumption of the transceiver is 0.35 W. Output power of the transmitter is 1 dBm with a 35-dB second harmonic suppression. Moreover, the on-chip isolations between T/R in this compacted transceiver are more than 60 dB. The measured receiver gain and NF are -4.5 and 11.5 dB, respectively. Finally, the obtained in-phase and quadrature signals demonstrate 0.6-dB amplitude and 7deg phase imbalance. [J17]

"A 77-GHz FMCW MIMO Radar Based on an SiGe Single-Chip Transceiver"

This paper describes a novel frequency-modulated continuous-wave radar concept, where methods like nonuniform sparse antenna arrays and multiple-input multiple-output techniques are used to improve the angular resolution of the proposed system. To demonstrate the practical feasibility using standard production techniques, a prototype sensor using a novel four-channel single-chip radar transceiver in combination with differential patch antenna arrays was realized on off-the-shelf RF substrate. Furthermore, to demonstrate its practical applicability, the assembled system was tested in real world measurement scenarios in conjunction with the presented efficient signal processing algorithms. [J18]

"Design of X-band complementary metal-oxide semiconductor-based frequency-modulation continuous-wave sensor"

This study presents an X-band complementary metal-oxide semiconductor-based frequency-modulation continuous-wave (FMCW) sensor system for transportation management. The proposed sensor system has two antennas, one to transmit signals and the other to receive them. The complete radio frequency (RF) transceiver

is based on standard 0.18 m one-poly six-metal (1P6M) CMOS technology with a chip area of 1.68 mm 1.6 mm. Two planar leaky-mode antenna arrays with a gain of 18 dB are also designed. Experimental results indicate that the isolation between two antenna arrays that are 5.0 mm apart exceeds 42.0 dB at 10.5 GHz. The prototype of the FMCW sensor system is used in the range measurement of multiple lanes for the transportation management system (TMS). The major contribution of this study is that it integrates a 0.18 m CMOS transceiver and antenna arrays into an FMCW RF front end, and employs an IF amplifier and a digital signal processor to demonstrate that the beat frequencies are linear. Measurements made in field tests agree closely with the simulation results. [J19]

"Interleaved Array Antennas for FMCW Radar Applications"

An effective and robust strategy for concurrently designing the transmit and receive antennas of a frequency-modulated, continuos-wave radar is discussed. The aperture architecture is based on the use of non-periodic, interleaved sub-arrays. Deterministic element placement is employed for ensuring design efficiency. The procedure yields controllable sub-array radiation patterns and two-way side-lobe levels below-30 dB, that are also stable over a wide frequency range. [J20]

"Millimeter-Wave Sensor With FMICW Capabilities for Medium-Range High-Resolution Radars"

Frequency-modulated continuous-wave (FMCW) radars offer many advantages such as low peak power, low probability of interception, low interference with other systems, and high-range resolution. However, their major drawback is the isolation required between the transmitter and receiver that typically leads to the use of two separate antennas for transmission and reception. Some schemes have been proposed to enable FMCW radars to operate with a single antenna, such as frequency-modulated interrupted continuous-wave (FMICW) technology. Recently, a stagger procedure has been proposed to overcome the problems associated with the use of the FMICW technique in high-resolution radars. The technique was tested using simulated data. Now, a high-resolution millimeter-wave radar sensor, in Ka-band, has been developed at the Universidad Politecnica de Madrid, Madrid, Spain, to perform an experimental validation of the theoretical approach of the stagger procedure. The sensor transmits a linear frequency-modulated interrupted continuous wave with a maximum bandwidth of 2 GHz and a transmitted power of +29 dBm. [J21]

"Millimeter-Wave-Radar Sensor Based on a Transceiver Array for Automotive Applications"

This paper describes a new radar sensor architecture comprising an array of transceiver modules. Target applications of the sensor are automotive driver assistance systems. In conjunction with a monolithic integration of each transceiver, the concept offers the possibility for a cost-effective realization of digital-beamforming radar sensors at millimeter-wave frequencies. A modulation sequence is investigated based on simultaneously transmitted frequency-modulated continuous-wave signals, which are separated by frequency multiplexing. Appropriate signal processing for the estimation of range, speed, and azimuth angle in multiple object situations is presented. Experimental results with an eight-channel radar sensor in the 76-77-GHz frequency band are presented, which demonstrate the feasibility of the proposed architecture and show the performance of the modulation sequence and signal processing. [J22]

"24-GHz Frequency-Modulation Continuous-Wave Radar Front-End System-on-Substrate"

Design and implementation of a 24-GHz frequency-modulation continuous-wave radar front-end system is presented and discussed, and its hybrid planar and waveguide building blocks are fully integrated on one single substrate. A flexible and compact integration methodology on the basis of the substrate-integrated-circuits concept is deployed to design such a microwave front-end system-on-substrate. In this study, it is found that this surface-volume hybrid integration scheme not only enables the complete system integration of planar and nonplanar microwave circuits, but also combines respective advantages of such structures in connection with microstrip lines (planar) and waveguides (nonplanar). Design strategies of the system building blocks including mixers, power dividers, and antenna arrays are discussed together along with the measured results. To verify the developed radar prototype, laboratory-based target-range measurements are conducted. [J23]

"Measurement of Distance and Medium Velocity Using Frequency-Modulated Sound/Ultrasound"

The methods reported for the measurement of distance and medium velocity using ultrasound are based on the principles of pulse radar, pulse Doppler radar, and continuous- wave radar. In this paper, the use of frequency-modulated sonic/ultrasonic radiations for such measurements has been proposed. The required measurement setup has been described, and the mathematical model needed for extraction of distance/medium velocity from the electrical output signal has been developed. The proposed measurement setup has been implemented for distance measurement with commonly used ICs. [J24]

"PRISM: An In-Vehicle CPU-Oriented Novel Azimuth Estimation Technique for Electronic-Scan 76-GHz Adaptive-Cruise-Control Radar System"

In this paper, we have developed a novel azimuth- estimation technique for 76-GHz adaptive-cruise-control radar systems. To resolve the rank deficiency of the signal covariance matrix and to decrease the influence of dominant noise components, we used an improved SS technique. To balance computational cost with azimuth resolution for in-vehicle implementation, we introduced a projection matrix kernel, which formally is similar to that of beamforming (BF) and semantically similar to that of the propagator method. Our technique is called the PRopagator method based on an improved spatial-smoothing matrix (PRISM). Incorrectly estimating the number of targets causes the conventional BF, subspace-based (SB), or maximum- likelihood methods to produce many false spectrum peaks on the relative azimuth-to-distance plane. We omitted the process of estimating the number of targets, which requires high computational power, because our projection matrix kernel strongly suppresses these false peaks. We conducted numerical experiments using an electronic-scan radar system to examine the performance of PRISM. Compared to conventional SB methods, PRISM requires SNRs that are 2-3 dB higher but has competitive azimuth resolution at a centesimal fraction of the computational cost. [J25]

"Software-Defined Six-Port Radar Technique for Precision Range Measurements"

A software-defined radar measurement system on the basis of a six-port receiver technique is proposed and described in this paper. The system makes use of a hybrid scheme of two performance-complementary operating modes, namely, frequency-modulated continuous-wave (FMCW) and two-tone continuous-wave signals. Generally, the FMCW-based measurement technique is deployed to give an approximate range value of target while the two-tone continuous-wave (CW)-based measurement technique can accurately determine the range that may, however, be ambiguous. The six-port circuit is used for the receiver as a precision phase detector in two-tone CW function and at the same time as a mixer in FMCW function. Various waveforms are generated in direct digital synthesizers and processed by different algorithms in a digital signal processor. The switching between the frequency-modulated CW and two-tone CW functions is controlled by software to improve the resolution and ensure a reliable operation. A system prototype is designed and made for a C-band demonstration. The Schottky diodes used as power detectors in the six-port are calibrated so that they can be used beyond the square-law region, thus allowing a higher power level and a better dynamic range. Measured results validate the proposed software-defined platform and accurate range results are confirmed. [J26]

"A Single-Ended Fully Integrated SiGe 77/79 GHz Receiver for Automotive Radar"

A single-ended 77/79 GHz monolithic microwave integrated circuit (MMIC) receiver has been developed in SiGe HBT technology for frequency-modulated continuous-wave (FMCW) automotive radars. The single-ended receiver chip consists of the first reported SiGe 77/79 GHz single-ended cascode low noise amplifier (LNA), the improved single-ended RF double-balanced down-conversion 77/79 GHz micromixer, and the modified differential Colpitts 77/79 GHz voltage controlled oscillator (VCO). The LNA presents 20/21.7 dB gain and mixer has 13.4/7 dB gain at 77/79 GHz, and the VCO oscillates from 79 to 82 GHz before it is tuned by cutting the transmission line ladder, and it centres around 77 GHz with a tuning range of 3.8 GHz for the whole ambient temperature variation range from -40degC to +125degC after we cut the lines by tungsten-carbide needles. Phase noise is -90 dBc/Hz@l MHz offset. Differential output power delivered by the VCO is 5 dBm, which is an optimum level to drive the mixer. The receiver occupies 0.5 mm2without pads and 1.26 mm2with pads, and consumes 595 mW. The measurement of the whole receiver at 79 GHz shows 20-26 dB gain in the linear region with stable IF output signal. The input P1dBof the receiver is -35 dBm. [J27]

"A Low-Power High-Sensitivity X-Band Rail SAR Imaging System [JMeasurement's Corner]"

Wideband radar imaging with range gating and high sensitivity can be achieved with the use of low-cost commercially available narrowband IF filters. Such filters reduce the effective receiver noise bandwidth of the radar system. This allows for high sensitivity, comparable to that of single-sideband radio receivers, while at the same time acquiring de-chirped wide-band received waveforms. A carefully developed radar architecture, based on the use of these IF filters, is shown in this paper. This radar architecture is then implemented in an X-band linear rail synthetic-aperture-radar (SAR) imaging system. The X- band rail SAR is a linear FM-chirped radar, which chirps from approximately 7.5 GHz to 12.5 GHz. The radar front end is mounted onto an eight-foot-long linear rail. The transmitted power is adjustable to 10dBm or less. It will be shown that objects as small as groups of pushpins in free space can be imaged using transmitted power as low as 10 nW. These results are compared to previous direct-conversion X-band FMCW rail SAR work. A high-sensitivity X-band rail SAR such as this could be useful for measuring low-radar-cross-section (RCS) targets. This radar could be used in high clutter environments that require a range gate. This low-power X-band rail SAR could be useful for operation in

restricted transmission areas, where maximum radiated power is severely limited. Other applications include any that require low transmitter power, such as automotive radar. [J28]

"A High-Resolution Imaging Radar at 580 GHz"

We have developed a high-resolution imaging radar at 580 GHz. Coherent illumination in the 576-589 GHz range and phase-sensitive detection are implemented in an all-solid-state design based on Schottky diode sensors and sources. By employing the frequency-modulated continuous wave (FMCW) radar technique, we achieve centimeter-scale range resolution while utilizing fractional bandwidths of less than 3%. Our high operating frequencies also permit centimeter-scale cross-range resolution at several-meter standoff distances without large apertures. Scanning of a single-pixel transceiver enables targets to be rapidly mapped in three dimensions, and here we apply this technology to the detection of concealed objects on persons. [J29]

"High-Resolution Estimation of Ranges Using Multiple-Frequency CW Radar"

The problem of ranging multiple vehicles traveling at similar speeds using multiple-frequency continuous-wave (CW) radar is considered. A new method based on the compensation of vehicle movement and MUSIC-based time delay estimator is presented. The method is tested using a commercially available multiple-frequency CW radar sensor in real traffic situations. Test results show that the proposed method makes it possible to estimate the positions of two vehicles moving at similar speeds. Test results also demonstrate that under a given bandwidth, the multiple-frequency CW radar can provide about ten times higher resolution as compared with the coherent spread spectrum radar [J30]

"High Precision Radar Distance Measurements in Overmoded Circular Waveguides"

Distance measurements in overmoded waveguides are an important application for industrial radar systems. The accuracy of the measurements is deteriorated by the appearance of higher order modes in the metal tube, although the frequency-modulated continuous-wave method is used with a large bandwidth. This paper describes the problems caused by dispersion and multimode propagation and presents a solution in the form of mode-matched antennas for feeding the overmoded waveguide. It is shown that different modes, e.g., the H11and H01modes, are equally well suited for precision distance measurements, as is demonstrated both by simulations and measurements. [J31]

"Phase-Error Measurement and Compensation in PLL Frequency Synthesizers for FMCW Sensors—II: Theory"

Synthesizers for the generation of frequency- or phase-modulated signals are required in communications, sensing, and many other fields and applications. The widespread use of phase-locked loops (PLLs) as major building blocks in current systems requires accurate models and methods for eliminating the influence of statistical and deterministic errors in the synthesized signals. We propose a novel iterative phase-error-measurement and -compensation procedure applicable in PLL-based synthesizers, for which the mathematical background is presented, and a detailed algorithmic description is given in this work. From a mathematical PLL system model and its response to a periodic excitation by the modulating signal, a method for measuring the instantaneous output signal phase and the actual transfer function of the PLL is derived. It is shown how this knowledge can advantageously be used for pre-distorting the synthesizer input signal to eliminate deterministic errors and to obtain an accurate output phase curve. [J32]

"Mutual Interference of Millimeter-Wave Radar Systems"

This paper examines the probability that any millimeter-wave radar systems will interfere mutually by considering spatial, temporal, and operational frequency-related overlaps. It examines the nature and magnitude of the interference under different conditions and for different sensor types before concluding that in an overlapping frequency band, the probability that interference will occur is high. It goes on to demonstrate that, though there are some forms of interference that can be identified and controlled, there are others which are impossible to isolate, resulting in degraded target detection performance and tracking [J33]

"High-Speed FMCW Radar Frequency Synthesizer With DDS Based Linearization"

Recently, we introduced a software linearization technique for frequency-modulated continuous-wave (FMCW) radar applications using a nonlinear direct digital synthesizer based frequency source. In this letter, we present a method that uses this unconventional, cost efficient, basically nonlinear synthesizer concept, but is capable of linearizing the frequency chirp directly in hardware by means of defined sweep predistortion. Additionally, the concept is extended for the generation of defined nonlinear frequency courses and verified on measurements

with a 2.45-GHz FMCW radar prototype [J34]

"Phase-Error Measurement and Compensation in PLL Frequency Synthesizers for FMCW Sensors—I: Context and Application"

The synthesis of linear frequency sweeps or chirps is required, among others, in frequency-modulated continuous-wave radar systems for object position estimation. Low phase and frequency errors in sweeps with high bandwidth are a prerequisite for good accuracy and resolution, but, in certain applications where high measurement rates are desired, the additional demand for short sweep cycles has to be met. Transient phenomena in dynamic synthesizers as well as nonlinear system behavior usually cause unknown phase errors in the system output. For the class of phase-locked-loop (PLL)-based frequency synthesizers, a novel output phase-measurement method and dedicated circuitry are proposed that allow significant reduction of phase errors by adaptive input predistortion. The measurement procedure is implemented within the PLL control circuitry and does not require external equipment. The application of this method to PLL system identification and linearization of extremely short frequency sweeps is shown [J35]

"Improved nonlinear frequency scaling algorithm for squint FMCW SAR"

An improved nonlinear frequency scaling algorithm is proposed to process squint frequency modulated continuous wave synthetic aperture radar data. The algorithm uses a decimation technique to decrease the bandwidth of the signal introduced by the frequency scaling operation, effectively removing the range frequency aliasing. Simulated results show the validity of the algorithm. [J36]

"Signal Processing for FMCW SAR"

The combination of frequency-modulated continuous-wave (FMCW) technology and synthetic aperture radar (SAR) techniques leads to lightweight cost-effective imaging sensors of high resolution. One limiting factor to the use of FMCW sensors is the well-known presence of nonlinearities in the transmitted signal. This results in contrast- and range-resolution degradation, particularly when the system is intended for high-resolution long-range applications, as it is the case for SAR. This paper presents a novel processing solution, which solves the nonlinearity problem for the whole range profile. Additionally, the conventional stop-and-go approximation used in pulse-radar algorithms is not valid in FMCW SAR applications under certain circumstances. Therefore, the motion within the sweep needs to be taken into account. Analytical development of the FMCW SAR signal model, starting from the deramped signal and without using the stop-and-go approximation, is presented in this paper. The model is then applied to stripmap, spotlight, and single-transmitter/multiple-receiver digital-beamforming SAR operational mode. The proposed algorithms are verified by processing real FMCW SAR data collected with the demonstrator system built at the Delft University of Technology. [J37]

"Dynamic range improvements and measurements in radar systems"

The extension of the dynamic range performance of existing radar systems is integral to the requirement for current sensors to see deeper into clutter, that is, to detect weak signals (e.g. small targets) in the presence of strong interference (e.g. urban clutter signals). The rationale behind this requirement is that this additional capability greatly enhances the utility of military and commercial systems. Two approaches to improving the dynamic range of modern radar and surveillance receivers are described: (1) linearisation of intermodulation distortion (IMD) using digital post-distortion algorithms and (2) linearisation of IMD using frequency retranslation mixer (FRM). The experimental results presented illustrate that the digital post-distortion and FRM approaches are effective in providing IMD improvements for the hardware and test scenarios measured. The improvements measured ranged from 15 to 35 dB for narrowband signals to 2-6 dB for frequency-modulated continuous wave (FMCW) wideband signals. The digital post-distortion approach provided the greatest performance improvement when the input signals were between the analogue-to-digital converter full range and 20 dB below that level. The improvements measured for the FRM linearisation approach ranged from 20 to 25 dB for the narrowband two-tone tests and 16-18 dB for the wideband FMCW signal chirps. [J38]

"Stagger procedure to extend the frequency modulated interrupted continuous wave technique to high resolution radars"

Frequency modulated continuous wave (FMCW) radars offer many advantages such as low peak power, low probability of interception, low interference to other systems and high range resolution. However, their major drawback is the isolation required between transmitter and receiver that typically leads to the use of two separate antennas for transmission and reception. Some schemes have been proposed to enable FMCW radars to operate with a single antenna. Frequency modulated interrupted continuous wave (FMICW) is a possible

solution. However, some considerations must be taken into account before implementing this technique in high resolution radars because of the amount of bandwidth needed. The problems associated with the use of the FMICW technique in broadband radars are analysed and a staggering procedure is proposed to overcome them. This technique is tested using simulated data from a 1 GHz bandwidth millimetre wave sensor, currently under development. The results are compared against other single antenna configurations and the advantages of the staggering technique are shown. [J39]

"A Chirp Transform Algorithm for Processing Squint Mode FMCW SAR Data"

Frequency-modulated continuous-wave (FMCW) synthetic aperture radar (SAR) is a lightweight cost-effective high-resolution airborne imaging radar. In squint case, the frequency scaling algorithm, which is suitable for processing nonchirped raw data, cannot be used directly in FMCW SAR data processing because of low system sampling frequency. On the other hand, the continuous antenna motion of FMCW SAR can cause serious distortions in the reconstructed images. In this letter, an improved algorithm called the chirp transform algorithm is proposed. When the effects of the residual video phase are negligible, the algorithm uses a chirp transform to perform the time scaling operation to alleviate the sampling frequency problem. It requires only fast Fourier transforms and multiplications. The range cell migration introduced by the continuous motion is also compensated completely in range-Doppler domain. The algorithm performances are analyzed and are supported by point target simulation experiments. [J40]

"Comparison of detectability of radar compression waveforms in classic passive receivers"

Several types of passive receivers can be used to detect radar emissions over considerable distances. Previous work has been performed which compares the detectability of bi-phase waveforms to a classic rectangular pulse. It is also of interest to compare the detectability of equal-bandwidth/equal-energy FMCW, quadriphase, and polyphase waveforms. The quadriphase waveform is the quadriphase version of the bi-phase Welti code. The polyphase waveforms are the PI, P2, P3, and P4 codes. Relative detection ranges are predicted using a simulation of the square-law, wideband crystal video, and channelized passive receivers possessing typical bandwidth, noise-floor, and loss parameters. A comparison is given showing the relative LPI/LPD attributes of each waveform and the relative detection attributes of each receiver. [J41]

"Synthetic aperture radar imaging using a unique approach to frequency-modulated continuous-wave radar design"

Synthetic-aperture-radar (SAR) imaging is an expensive endeavor. It can be difficult for universities, small business, or individuals to experiment with SAR imaging and algorithm development on a low budget. For this reason, a uniquely inexpensive solution to frequency-modulated continuous-wave (FMCW) radar was developed and then utilized as an ultra-low-cost SAR imaging system. This unique approach to FMCW radar used a pair of low-cost Gunn-oscillator-based microwave transceiver modules, known as "Gunnplexers." These transceiver modules had stability and noise problems, causing them to be unsuitable for use in precise FMCW radar applications when just one module was used. In order to overcome this problem, a unique radar solution was developed that used a combination of two transceiver modules to create a precise and inexpensive FMCW radar system, capable of producing SAR imagery on a budget [J42]

"Ultra-lightweight synthetic aperture radar based on a 35 GHz FMCW sensor concept and online raw data transmission"

With the increasing number of small-size unmanned aerial vehicles (UAVs) for remote sensing, reconnaissance and surveillance applications, the demand for miniaturised and low weight synthetic aperture radar (SAR) sensor systems for these platforms has increased. Because of the extreme payload weight restrictions of unmanned platforms, size, weight and power (SWP) characteristics actually become dominating design drivers for UAV SAR developments. The author focuses on the development of a highly miniaturised SAR (MISAR) sensor that was especially designed for UAVs with stringent payload SWP constraints. The paper gives an overview of the design considerations for the MISAR sensor system. The realisation of the sensor is described and the results of test flights in fixed-wing aircraft, rotary-wing aircraft and in UAVs are presented. [J43]

"Signal model and linearization for nonlinear chirps in FMCW Radar SAW-ID tag request"

In this paper, we present a frequency-modulated continuous-wave radar interrogation concept, based on direct digital synthesis (DDS), that operates without the commonly necessary high-frequency DDS reference oscillator. As the generated frequency sweeps are nonlinear, standard Fourier transform methods for baseband signal evaluation cannot be applied directly. We show the corresponding signal model, derive a linearization concept on

the basis of resampling, and demonstrate the linearization algorithm on simulated data, as well as on real wireless interrogations of surface acoustic-wave sensors. [J44]

"An Efficient Method of Eliminating the Range Ambiguity for a Low-Cost FMCW Radar Using VCO Tuning Characteristics"

This paper describes a simple method of eliminating the range ambiguity and the design approach for low-cost and small-size homodyne frequency-modulated continuous-wave (FMCW) radars. The range measurement accuracy could be efficiently improved by proper time gating of the beat signal without any closed-loop linearity compensation circuitry for typical varactor-tuned voltage-controlled oscillators (VCOs). The presented selectively gated fast Fourier transformation method is immune to the frequency shift of the VCOs. A W-band FMCW radar using a raw varactor-tuned VCO having the percent linearity of 7.16% was implemented, and achieved less than 2% ranging error of the target lying at 200 m. Owing to the simple structure and fast processing speed, this method is applicable to the various low-cost radar sensors for ranging and detection [J45]

"A -Band FMCW Radar Front-End With Adaptive Leakage Cancellation"

Monostatic frequency modulation continuous wave radars that use one antenna to simultaneously transmit and receive can result in compact and lightweight synthetic aperture radar systems. One of the greatest challenges in designing a continuous-wave monostatic radar is realizing enough isolation between the transmitter and the receiver. A novel real-time digital signal processing scheme is proposed to cancel the transmitter leakage at the receiver front-end and to achieve high isolation. With the digital implementation, the proposed scheme shows a much more precise control of the leakage cancellation when compared to conventional analog implementations. The dc-offset problem in analog mixers that affects the cancellation performance is eliminated. A radar test bed at 26 GHz has been built and tested in several radar modes. The measurement shows a leakage suppression of more than 30 dB over a 1.7-GHz sweeping bandwidth [J46]

"Dual-polarised T/R antenna system suitable for FMCW altimeter radar applications"

The authors propose a dual-polarised T/R antenna system that utilises a 3 dB 90deg hybrid coupler and a dual-polarised antenna. From the practical point of view the T/R isolation performance of this system can be made better than that of systems using circulators. There is no power loss both in transmit and receive modes compared to 6 dB total loss in a conventional system using a hybrid coupler and a single polarised antenna. To validate the system performance, a sample structure is realised for a C band application. The presented system analysis and measurements are for an above-ground application. The measurements show good agreement with the theoretical expectations [J47]

"Narrow linewidth fiber laser for 100-km optical frequency domain reflectometry"

A diode-pumped single-frequency piezoelectrically tuned fiber laser with narrow spectral linewidth has been used as a light source in applications for long-range coherent frequency-domain reflectometry. Frequency-modulated continuous-wave (FMCW) measurements of Rayleigh back-scattering and Fresnel reflection from a 95-km-long fiber have been demonstrated without the use of an optical amplifier. This is, to our knowledge, the longest distance measurement with FMCW. The high sensitivity and dynamic range of the long-range backscattering measurements benefit from the extremely long coherence length of the narrow linewidth fiber laser, which has been estimated to be 210 km in air. [J48]

"Linear frequency modulation of voltage-controlled oscillator using delay-line feedback"

This letter proposes a structure for a voltage-controlled oscillator (VCO) circuit which operates in a frequency range of 4.0-4.3 GHz and can achieve a highly linear frequency sweep without any additional compensation circuit. The VCO consists of an amplifier and a feedback circuit only. The feedback circuit compensates for the phase delay of a transmission line with a varactor and sets the closed-loop phase change close to 360°. The measured maximum deviation from a linear frequency sweep is 1.2 MHz when the varactor capacitance CVof the VCO is related to the control voltage VCby CV VC-1.06. The spectral distribution of the beat frequency between the VCO output and delayed VCO output shows that the proposed VCO has excellent linearity in frequency modulation. [J49]

"W-band airborne interrupted frequency modulated CW imaging radar"

A 94 GHz imaging radar-based on the interrupted FMCW (FMICW) principles, with its associated gimbals for stabilization and scanning has been developed as an airborne test-bed to evaluate radar-aided navigation and guidance algorithms. Preliminary results from helicopter-based flight tests show sufficient contrast between

selected features (including runways) and their surroundings for both computer- and human-pilot-based guidance. Feature extraction and matching algorithms have shown this system to be more accurate than GPS. [J50]

"Integrated object and road border tracking using 77 GHz automotive radars"

Radar sensors are widely used in automotive on-board systems such as adaptive cruise control, which tracks the preceding vehicle and keeps a safe distance. The authors go a step further and exploit the potential of a high resolution radar sensor for the estimation of the road borders and the reconstruction of the traffic scenario based on object tracking. A FMCW millimetre wave radar is mounted in the front bumper of a vehicle and delivers object lists to the central fusion processor, where detections are considered as measurements to an integrated model based road border estimation system. The algorithm presented is designed to improve the prediction of paths and trajectories of the ego-vehicle in future enhanced collision warning and collision avoidance systems. Given the characteristics and limitations of a radar system, such as heavy clutter, the algorithms are tested with real data and perform reliably in highway and extra-urban scenarios and are competitive with data fusion and stereo vision systems, but with lower computational load. [J51]

"An efficient method for nonlinear distortion calculation of the AM and PM noise spectra of FMCW radar transmitters"

The demand for autonomous cruise control and collision warning/avoidance systems has increased in recent years. Many systems based on frequency-modulated continuous-wave (FMCW) radar have emerged and are still in development. Due to the high complexity of such systems, the accurate evaluation of the noise spectra in the transmitter chain driven by complex modulated signals is today a severe drawback due to the limitation of simulation tools. In this paper, a method is proposed to compute easily with any commercially available nonlinear simulator, the amplitude and phase modulated signal distortion introduced by the nonlinearities of the transmitter on an FMCW signal. First, the amplitude modulation (AM) and phase modulation (PM) noise spectra of the driving FMCW signal is derived from the knowledge of the continuous wave (CW) AM and PM noise spectra of the voltage-controlled oscillator (VCO), and the modulating saw-tooth signal applied. Using the narrow band envelope concept and a first-order expansion of the nonlinear transfer function of the transmitter, the transfer of the AM and PM noise spectra of the driving FMCW signal through the nonlinear transmitter chain and the resulting output distortion are then computed. This novel approach allows to compute with reduced computation time and very good accuracy the AM/AM, AM/PM, PM/PM, and PM/AM conversion terms in any nonlinear system driven by CW or FMCW signals. This new method has been applied to the characterization of a whole car radar transmitter operating at 77 GHz driven by an FMCW signal issuing from a VCO. A successful comparison between measured and simulated PM-to-AM conversion coefficients of this transmitter is shown, validating the proposed method. [J52]

"A high precision 24-GHz FMCW radar based on a fractional-N ramp-PLL"

A 24-GHz FMCW radar system is presented using a fractional-N phase-locked loop ramp generator. This fractional-N ramp generator achieves relative ramp nonlinearities below 10-8. Among others linear frequency ramps are important tools in high precision FMCW radar systems. Highly linear frequency ramps make post measurement error correction feasible. Other important aspects of the high performance FMCW radar system are the design of the microwave circuit and the digital signal processing of the IF signals. Furthermore, a large RF bandwidth of more than 3 GHz obtained by thorough simulations results in a high range resolution and a good potential measurement accuracy. To maintain this high potential accuracy, a phase slope algorithm is used to calculate the precise range value leading to a significantly better precision with absolute range errors below 0.8 mm, compared to the commonly used spectral center algorithm. [J53]

"Single-stage photodiode op-amp solution suited for a self-mixing FMCW system"

The current delivered by the photodiode in a self-mixing frequency modulated continuous wave or optical frequency domain reflectometry system consists of a dc-current resulting from the local oscillator, the reflected signal, dark current in the photodiode, and current generated from background light. The current also contains the useful harmonic signal with a beat frequency corresponding to the range and radial velocity of a target. To avoid saturation and clipping due to the dc current generated in the photodiode, it is desirable to minimize the gain at dc while maintaining a high gain in the beat frequency region. We have investigated some different solutions and present a modified current-to-voltage converter using bootstrapping and added voltage gain, which addresses this problem using only one OP-amp and no dc shorting inductors. [J54]

"Doppler estimator operating with matched filter for vehicular spread spectrum radar"

A Doppler estimator is designed for vehicular spread spectrum radar operating with the matched filter. Simulation results demonstrate that the estimated error of the relative speed between the leading car and the host car decreases with the relative speed. The maximum estimated error of the relative speed could be reduced to ±0.15 km/h within 0.84667 μs processing time [J55]

"A balanced FET FMCW radar transceiver with improved AM noise performance"

A balanced FET frequency-modulated continuous-wave radar transceiver designed to suppress AM noise is presented. The transceiver utilizes the same device for output power amplification as for down-conversion of the received signal, thereby avoiding the need for separation of these signals. This makes the transceiver suitable for integration in monolithic-microwave integrated-circuit technology. A test circuit operating at 10 GHz was designed. The AM noise suppression is characterized, as well as output power and noise performance. Comparison with an unbalanced transceiver using the same principle of operation shows an improvement of 20 dB in AM noise performance. The output power is 14 dBm at 7-dBm input power [J56]

"Compact single-chip W-band FMCW radar modules for commercial high-resolution sensor applications"

Two compact single-chip 94-GHz frequency-modulated continuous-wave (FMCW) radar modules have been developed for high-resolution sensing under adverse conditions and environments. The first module contains a monolithic microwave integrated circuit (MMIC) consisting of a mechanically and electrically tunable voltage-controlled oscillator (VCO) with a buffer amplifier, 10-dB coupler, medium-power and a low-noise amplifier, balanced rat-race high electron-mobility transistor (HEMT) diode mixer, and a driver amplifier to increase the local-oscillator signal level. The overall chip-size of the FMCW radar MMIC is 2Ч3.5 mm2. For use with a single transmit-receive antenna, a 94-GHz microstrip hexaferrite circulator was implemented in the module. The radar sensor achieved a tuning range of 1 GHz, an output signal power of 1.5 mW, and a conversion loss of 2 dB. The second FMCW radar sensor uses an MMIC consisting of a varactor-tuned VCO with injection port, very compact transmit and receive amplifiers, and a single-ended resistive mixer. To enable single-antenna operation, the external circulator was replaced by a combination of a Wilkinson divider and a Lange coupler integrated on the MMIC. The circuit features coplanar technology and cascode HEMTs for compact size and low cost. These techniques result in a particularly small overall chip-size of only 2Ч3 mm2. The packaged 94-GHz FMCW radar module achieved a tuning range of 6 GHz, an output signal power of 1.5 mW, and a conversion loss of 5 dB. The RF performance of the radar module was successfully verified by real-time monitoring the time flow of a gas-assisted injection molding process. [J57]

"Implementation of reflectometry as a standard density profile diagnostic on DIII-D"

The profile reflectometer system on the DIII-D tokamak has been significantly upgraded in order to improve time coverage, data quality, and profile availability. The performance of the reflectometer system, which utilizes continuous frequency modulated (FMCW) radar techniques, has been improved as follows: First, a new PC-based data acquisition system has been installed, providing higher data sampling rates and larger memory depth. The higher sampling rate enables use of faster frequency sweeps of the FMCW microwave source, improving time resolution, and increasing profile accuracy. The larger memory depth enables longer data records, so that profiles can now be obtained throughout 5 s discharges at 100 Hz profile measurement rates, while continuous sampling at 10 MHz is available for 1 s for high time resolution physics studies. Second, an initial automated between-shots profile analysis capability is now available. Third, availability of the profiles to end users has been significantly improved. copyright 2001 American Institute of Physics. [J58]

"Radar backscatter from mechanically generated transient breaking waves. II. Azimuthal and grazing angle dependence"

For Pt. I see ibid. vol. 26, pp. 181-200 (2001). This paper describes the results of experimental investigations into the microwave backscatter from mechanically generated transient breaking waves. The investigations were carried out in a 110 mЧ7.6 mЧ4 m deep model basin, utilizing chirped wave packets spanning 0.75-1.75 Hz. Backscatter measurements were taken by a K-band continuous wave radar (24.125 GHz) at 40° angle of incidence, and at azimuth angles of 0°, 45°, 90°, 135° and 180° relative to the direction of wave propagation. Grazing measurements were conducted using an X-band (10.525 GHz) FMCW radar at 85° angle of incidence, and azimuth angles of 0° and 180°. Results show that the maximum radar backscatter was obtained in the upwave direction prior to wave breaking and was caused by the specular or near specular presentation of the wave to the radar. After breaking, the backscatter transitioned from a specular or near-specular dominated scattering, primarily seen in the upwave direction, to a small scale roughness dominated scattering, observed at all azimuths. Physical optics solutions were found to correctly predict the backscatter for the specular or near-

specular dominated scattering and the small perturbation method was found to accurately model the VV polarization post-break radar backscatter [J59]

"Design, fabrication, and application of precise SAW delay lines used in an FMCW radar system"

An inexpensive frequency-modulated continuous-wave (FMCW) radar system is presented in this paper, which, nevertheless, meets all industrial requirements. The FMCW radar uses a low-cost nonlinear voltage-controlled oscillator (VCO), operating at an IF of 2.45 GHz to generate the frequency modulation of the radar system. This VCO signal is applied twice, first to generate the radar transmitter signal at 24 GHz, and then it is fed to a surface acoustic wave (SAW) delay line. The SAW delay line generates a fixed delay time, which corresponds with a fixed radar distance. Thus, all systematic nonlinearities and stochastic phase errors of the FMCW system can be monitored and, afterwards, can be compensated for in real time. This linearization technique leads to a significant enhancement in dynamic range for a FMCW radar system. For this FMCW system, SAW delay lines with a linear phase characteristic have been designed using a linear optimization program. The delay line consists of two chirped and weighted interdigital transducers. For high volume, low-cost, and high-yield production of the required SAW structures, with linewidths down to 0.3 µm, technological improvements had to be achieved, especially in photolithography. Based on these design and fabrication techniques, delay lines at 2.45 GHz operating at the fundamental and third harmonic with bandwidths up to 800 MHz have been realized [J60]

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