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Guided Wave Radar for Precise level Measurement using Time Domain Reflectrometry (TDR) Principle

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ABSTRACT: In the radar level measurement instruments, the electromagnetic signal travel through air. Once it touches the material under test, it gets reflected back to the input end. The reflection of electromagnetic signal depends on electric and dielectric properties of material. Guided Wave Radar (GWR) meter isbased on the Time Domain Reflectrometry (TDR) principle for precise level measurement. TDR, which is well known measurement technique in telecommunication industries for evaluating electric and dielectric property of various material, used for precise level measurement and fault detection. Despite all advancement made within the last few years, there is still lack of low cost, small TDR meter equipment in market. This paper proposes a designon the development of a new miniaturized low-cost TDR meter capable of sampling a repetitive rectangular waveform, which is used as an excitation signal. The key techniques of pulse generation and time measurement are introduced with the selection of GWR probe for accuracy even when the measurement within a highly unstable environment. The signal generation with fast rising time is accomplished using small electronic circuit and the basic laboratory setup.Generally, there is a need of a high resolution, low power consuming, miniature TDR for dynamic level measurement in petrochemical, oil tank and shipbuilding industries application. Experimental results indicate the feasibility and improved functionality of the system.

KEYWORDS: Time Domain Reflectometry (TDR), equivalent sequential time sampling, transit time, waveguide selection.

I. INTRODUCTION

Guided Wave Radar (GWR) is a well-known technique in sensor Instrumentation Industries, for high precision level measurement [1],[2] and [4]. Comparing with traditional radar measurements techniques like RF capacitance unguided radar meter and ultrasonic meter etc., the guided radar meter is widely used to dynamically monitor the level [2] and [3]. Before we can decide which one is best out of them, however, we need to understand how each works and the theory behind it in short. In RF capacitance, a capacitor consists of two conductors (plates) that are electrically isolated from one another by a non-conductor (dielectric) [10]. When the two conductors are at different potentials (voltages), the system is capable of storing an electric charge. The dielectric constant of a substance is proportional to its admittance. The lower the dielectric constant, the lower the admittance of the material (that is, the less conductive it is). Capacitance (C) is calculated as:

$$C = \frac{KA}{D} \qquad (1)$$

If the area (A) of and the distance (D) between the plates of a capacitor remain constant, capacitance will vary only as a function of the dielectric constant of the substance filling the gap between the plates. If a change in level causes a

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change in the total dielectric of the capacitance system, because the lower part of area (A) is exposed to a liquid (dielectric K_l) while the upper part is in contact with a vapour (dielectric K_v, which is close to 1.0), the capacitance measurement will be proportional to level. The disadvantages of this method are time consuming and not used in Continuous level measurement.

Radar methods of level measurement are sometimes referred to as microwave types. Both use electromagnetic waves, typically in the microwave X-band (10 GHz) range. Most applications have been designed for continuous level measurement. Basically, the unguided radar and ultrasonic radar types operate on the principle of beaming microwaves downward from a sensor located on top of the vessel. The sensor receives back a portion of the energy that is reflected off the surface of the measured medium. Travel time for the signal (called the time of flight) is used to determine level. For continuous level measurement, there are two main types of Antennas for this methods come in two designs: parabolic dish and cone. The parabolic dish antenna tends to direct the signals over a wider area while the cone tends to confine the signals in a narrower downward path. The choice of one or the other, and its diameter, depends on application factors. While both ultrasonic and sonic level instruments operate on the basic principle of using sound waves to determine fluid level. The frequency range for ultrasonic methods is ~20–200 kHz, and sonic types use a frequency of 10 kHz.

Despite all advancements achieved within past few years, but the problems like time consuming and dispersion of radar beams at the receiverwith above method are not overcome by any techniques. To solve dispersion of radar beams and as for as small thank application concern the guided GWR meter technique is introduced. Guided-wave radar is a method that uses a metallic rod or coaxial cable to guide the micro wave as it passes down from the sensor into the material being measured and all the way to the bottom of the vessel.

The basis for GWR is Time-Domain Reflectometry(TDR), which has been used for years to locate breaks in long lengths of cable that are underground or in building walls [4],[5]. A TDR generator develops more than 200,000 pulses of electromagnetic energy that travel down the waveguide and back. The dielectric of the measured fluid causes a change in impedance that in turn develops a wave reflection. Transit time of pulses down and back is used as a measure of level also called as transit time or time of flight.

Despite TDR-based measurement systems having been successfully used thousand times within research industries and telecommunication field, there is still lack of availability of low cost, low power consuming TDR in market, particularly in outdoor monitoring applications. The price of most well-known TDR meters such as theVegaflex 82, Tektronix 1502C, or the Mohr Scientific CT100typically is in the range of several thousand dollars.The Campbell Scientific TDR100 meter often found in agricultural application to measure percentage of moisture in soil.However, most available TDR meters are designed and optimized for laboratory use only and therefore have large size, high power consumption, and are not well suited for outdoor use. This paper proposes a design leads to development of low cost TDR meter with high resolution.

II. RELATED WORK

In recent past years, many ideas have been presented related to design and development of innovative TDR meters. Dennis Trebbels*et.al.*,[1] have design theFPGA based new miniaturized low-cost TDR meter capable of sampling a repetitive rectangular waveform, which is used as an excitation signal. The author also integrate the TDR meter with microcontroller and a real-time clock and therefore can operate completely independent from any additional control setup. But a drawback of the system is the requirement of external calibration and it is used only in geological application.

Jun Gu *et.al.*,[2],[4] proposed an exact method far level measurement based on guided wave radar meter using equivalent time sampling. But the system is for low measurement resolution.JoergHuettner proposed a low cost Ultra-Wide-Band Pulse Radar in a guided wave gauging application. According to the [3], the temporal sampling resolution is 250ps that shows a resolution of 6.5 cm. Xudong*et al.* developed a TDR-based cable fault diagnosis system, but the system was implemented using expensive off-the-shelf laboratory equipment such as a pulse generator and a fast

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sampling oscilloscope [11],[9].EckhardDenicke*et.al.*, [7] and [8] proposed a Correlation-Based Method for Precise Radar Distance Measurements in Dispersive Waveguides,where he explain and simulate TDR on the transmission line theory, but it required two stable waveguides for measurements.

III. PROPOSED SYSTEM PRINCIPLE

The level measurement is widely used in the areas, where liquid level under constant change like petrochemical, shipbuilding industries, oil tanks, etc. Such dynamic level measurement accomplished by guided wave radar meter using TDR principle. Generally, TDR utilized the periodic narrow pulses or rectangular square wave pulses with sharp rising and fast falling edges. The principle is work by transmitting pulses along the application based waveguide probe such as open ended co-axial lines or metal rod or ribbon cable or stainless steel tube. It get reflected and received at to input end, due to sudden change in characteristic impedance take place, when pulse wave hit the surface of material under test. The resulting time of incident (send) and reflection (received) captured with high resolution, which used to calculate the transit time ΔT and corresponding height of material as

$$H = \frac{\Delta T \text{ X } V}{2} (2)$$

Where, H is height of material, V is propagation velocity of pulse wave inside the waveguide,ΔT is transit time.

IV. SYSTEM ARCHITECTURE

The goal of new TDR meter is to capture waveform with high resolution.To get fast measurement, the ΔT should be in nanosecond (ns) range. In real time, by using direct measurement technique it is impossible to measure the nanosecond range ΔT. To get precise measurement of level, the time measurement capacity should be in picosecond (ps) range. To achieve ps resolution the reflected wave signal is expanded by using equivalent sequential time sampling. The architecture of guided wave radar meter is shown as Fig 2. Which consists of signal generation, signal processing, microcontroller unit, display, USB connector and waveguide.

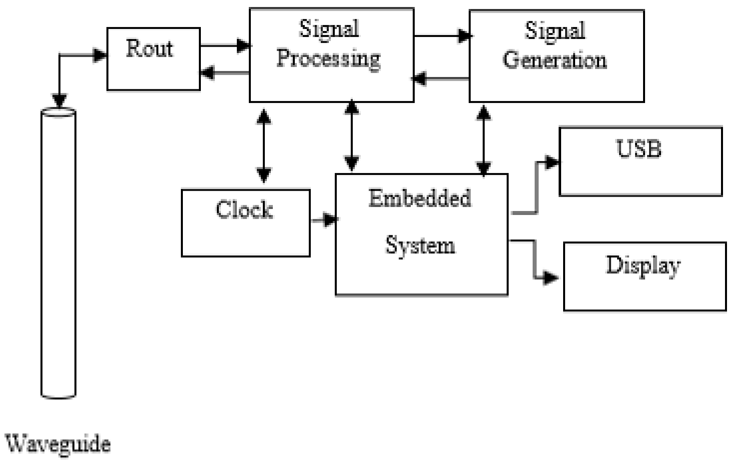

Fig 1Architectural design of guided wave radar meter

The pulse generation is accomplished with signal generation unit, a fast rising edge is generated. This fast rising edge pulse is travel through the waveguide. The reflection is get back at the input end when it reaches the surface of impedance mismatch and is measured. To get measurement in the resolution of picosecond (ps), calibration is needed and which is done by using clock measurement for end and middle probe reflection as a reference. The key component of TDR is signal processing for precise measurement with high resolution. USB and Display are used to store and display the measured reading respectively.

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V. SELECTION OF WAVEGUIDE

Selection of waveguide is also very important factor which is depend on different application. Furthermore, in geological and agricultural application the flat ribbons are used as waveguide, while in many level meter the metal coaxial probe are used. As far as project application concern, we are using 2 m stainless steel (SS) probe as transmission line. As compared to float system, SS probe is immune to mechanical shock and more resistant to corrosion.

Fig 2. 2m Stainless steel waveguide testing with characteristic impedance of 50 Ω in air.

The probe consist inner conductor, an outer conductor and an insulator provides electrical isolation between them. The general impedance equation of a coax cable is:

$$Zs = \frac{1}{2\pi} \frac{\sqrt{\mu o \mu r}}{\sqrt{\varepsilon o \varepsilon r}} \times \ln \frac{Do}{Di} \qquad (3)$$

Where,
μois the free space magnetic permeability
μris the relative permeability of the conductors
εois the free space dielectric permeability
εris the relative dielectric of the insulating material
$D_o$is the outer conductor diameter, $D_i$is the inner conductor diameter

μo,μr and εo are taken as constant and their values are known. According to mathematical measurement, the outer diameter of Stainless steel (SS) tube of length 78.74" is 0.455". This is generated using a total diameter of 0.62992" and with a 0.08745" wall thickness of SS tube. The SS probe is constructed with inner diameter of 0.1968 and air as the insulator, where εr is 1. Using all parameters of equation 2, we get

$$Zs = \frac{50.25}{\sqrt{\varepsilon r}} \approx 50\Omega \qquad (4)$$

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TABLE 1-Design parameter of SS probe

Parameter	Description	Optimal Value
D_o	Outer SS tube diameter	0.455”
D_i	Inner SS rod diameter	0.1968”
L	Length of a SS probe	78.74”
Z_s	Impedance of SS probe	50.25 Ω

The effect of temperature on SS coaxial probe with air insulator is negligible. High temperature or large temperature gradients have very little effect on the transit time of microwaves within an air or vapour space. At a temperature of 2000° C the variation is only 0.026% from the measurement value at 0° C.

VI. SIGNAL GENERATION AND SIGNAL PROCESSING

The most important and critical part of guided radar level meter measurement is signal generation and signal processing for precise distance measurement with high accuracy. The signal generation is accomplished using signal generator with fast rising time.If the wave will propagate about 4 inches in 1ns and if we use rise time of 1 ns then any reflection between 4 inches will gives attenuation in the edge of the pulse. The increase in rise time produce less resolution and we can’t figure out the sending and reflected pulse as a separate pulse. Hence the minimum distance measurement will drop to 4 inches, to neglect such consequence, we need to generate fast rising pulse. Also, the pulse cycle (width) must be as small as possible so that the incident and the reflected wave can be differentiable. The fig 3(a), (b) and (c) shows the difference of small and large pulse width.

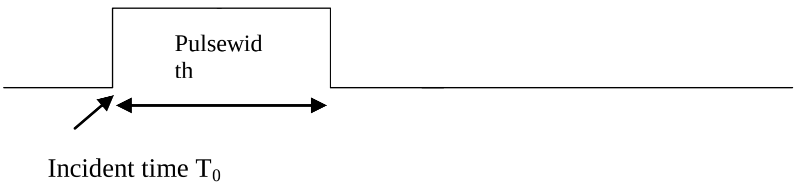
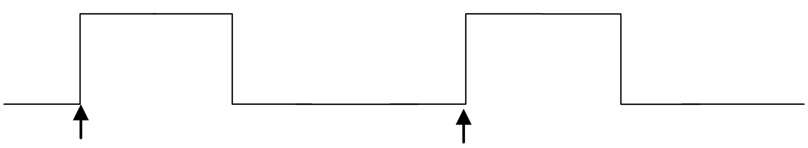


Fig 3(a)



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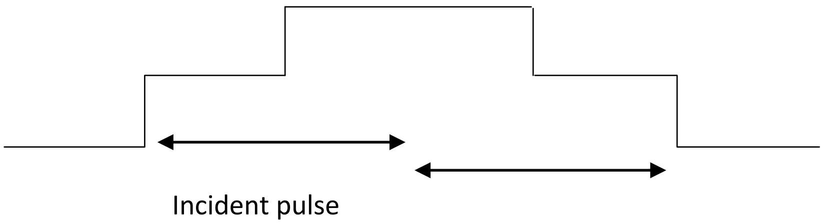

Fig 3(c)

Fig 3 (a) Incident rectangular input pulse with time T_0 , (b) Reflection due to impedance mismatch with small pulse width, (c) Effect of large pulse width on reflection due to change in impedance.

i. SIGNAL GENERATOR

The circuit shown in fig 4 is best powered with 4.5V battery or three 1.5V AA batteries connected in series. The + from battery goes to IC1 pin 14 of 74AC14. The pin 7 of IC1 is connected to circuit ground which is connected to circuit ground. Remember to put a 100 nF (ceramic or polypropylene) capacitor between IC1 pins 7 and 14 to guarantee stable operating voltage for the circuit. The performance limitations are seen most on the shortest pulse lengths. Normal BNC T-piece works quite well if directly plugged to the high impedance input of an oscilloscope (typical low cost oscilloscopes). For this circuit to work the cable to the oscilloscope should be short (20-30 cm). This circuit version that we built has two signal outputs, one for cable to be tested and another for the trigger. The resultant rectangular pulse generated with 2 µs rise time.

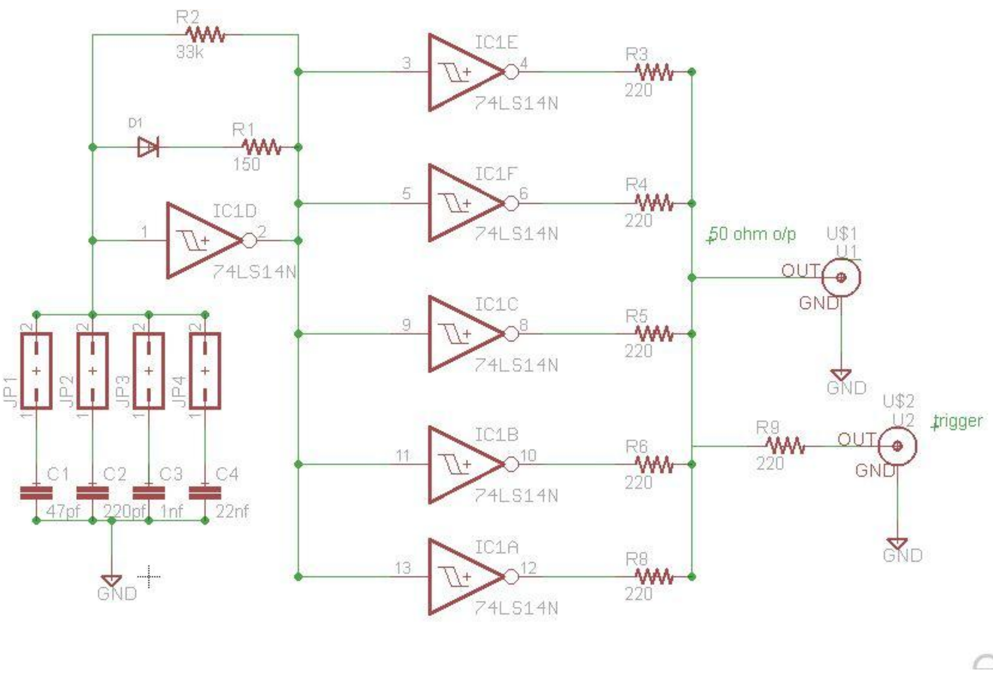

Fig 4 Circuit design for rectangular pulse wave generation with fast rise time.

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ii. SEQUENTIAL EQUIVALENT TIME SAMPLING

The sequential equivalent time sampler acquire one sample per trigger independent of time/div setting. When trigger is detected, a sample is taken after a very short, but well defined, delay.When the next trigger occur a small time increment - Δt is added to this delay and the digitizer takes another sample. These process repeated many times. We can use any standard sampling circuit made up of diodes and resisters.

In order to meet the high speed sampling requirement, a diode based single-tube sampling gate circuit with simple structure is used. Sampling gate uses the diode for its excellent switching performance. Technically, it is easier to generate very short, very precise Δt than it is to accurately measure the vertical and horizontal position of a sample relative to trigger point.

VII. LABORATORY EXPERIMENT 1

In laboratory experiment, the goal of the experiment is to test the return loss of the SS probeat different excitation signal frequencies and the calculation of characteristic impedance. At the beginning of the experiment, an open-ended 50-Ω SS probe with a length of 2 m is connected to the vector network analyzer(VNA). The output resistor *R*out is set to 50 Ω, which allows for comparing the device to other standard laboratory equipment having 50-Ω outputs. In addition, it allows for connecting a 50-Ω coaxial cable for defined and reproducible measurements. We are investigating the system behaviour at 6GHz and 7 GHz and 7.3 and 8 GHz. Lower frequencies lead to extremely long acquisition times and are not acceptable in our target applications. The frequency response shows the considerable return loss of 10dB and the characteristic impedance is near to 50-Ω.

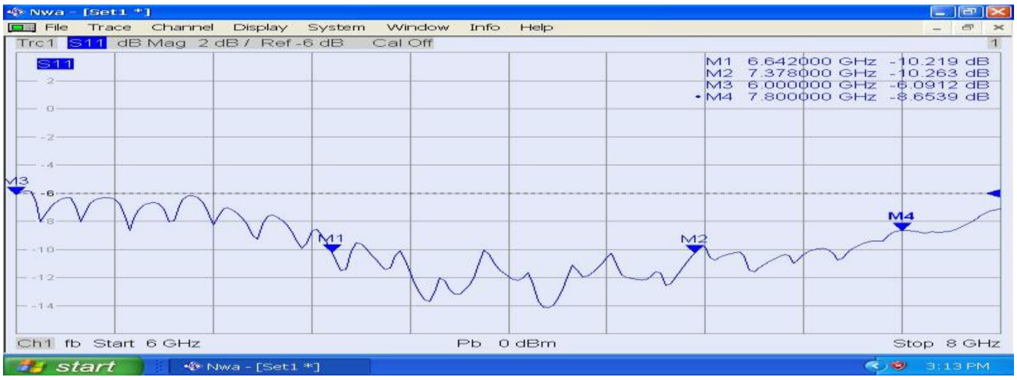

Fig 6 (a) Measured return loss of open ended 50-Ω SS probe at different frequencies

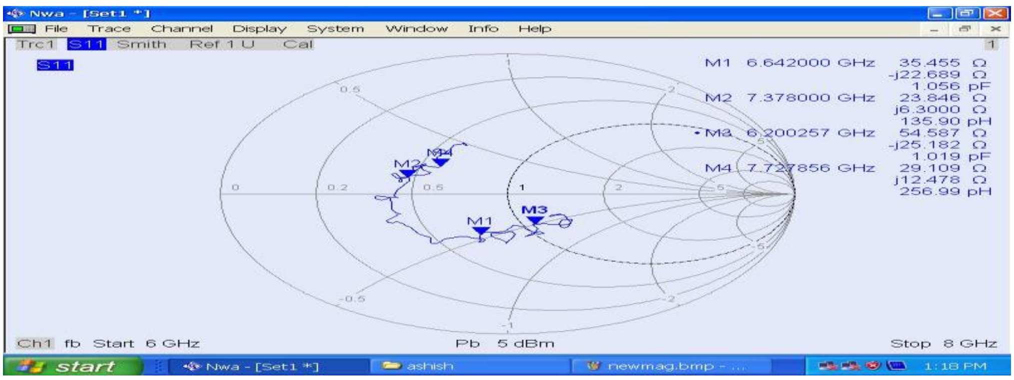

Fig 6(b) Smith chart for the calculation of characteristic impedance.

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(An ISO 3297: 2007 Certified Organization)

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VIII. LABORATORY EXPERIMENT 2

The general concept using laboratory setup based on excitation of pulse signal, which is fed into an open ended SS probe and fast sampling Oscilloscope is used for capturing the waveform of measurement signal connected using Normal BNC T-piece as shown in fig 5. The typical waveform at beginning and the resulting reflected waveform at air-liquid interface is shown in Fig 6. The measurement will be made by sending pulse through transmission probe and when the reflection from the material under test returns.

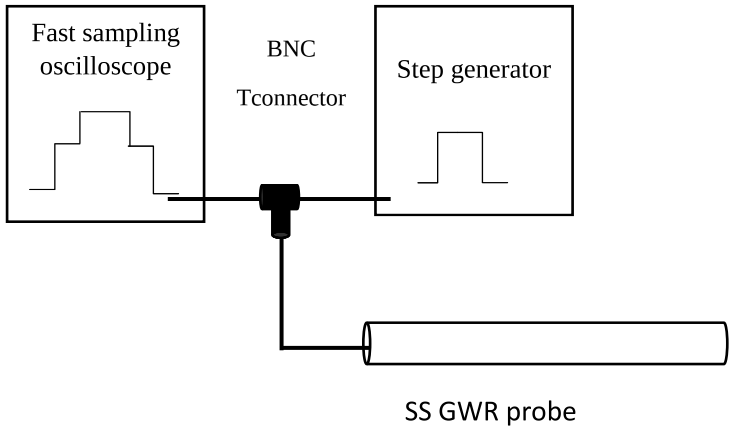

Fig 5 General laboratory setup for testing of signal generator and waveguide.

As the speed of light in free space is 11.8”/nsec and the velocity factor of SS probe is 0.5084, the speed of pulse travel down SS probe is 5.9”/nsec. If the time of incident and reflection is 15.76 nanosecond then the level of material under test can be calculated using following formula.

$$L = \frac{\Delta T \text{ X } V}{2} \qquad (7)$$

$$= \frac{15.76 \text{ X } 5.9}{2}$$

= 46.492 inches / 1.18 meter

Fig 6 the resulting incident and reflected waveform at air-liquid interface

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IX. CONCLUSION

This paper introduced an implementation of miniature, low cost GWR meter for high resolutionlevel measurement based on the principlesnamely TDR, radar and sequential equivalent time sampling techniques. It will provide self-calibration and independencefrom fluid type. The construction of stainless steel as a waveguide means no corrosion, more immune to mechanical shock and less cost as compare to ultrasonic sensor in unguided system. Resultsfrom the laboratory experiment 1 provide flexibility in frequency, used for pulse generation and also generate same impedance.In laboratory experiment 2, the rectangular pulse wave is generated with fast rising time and tested using fast sampling oscilloscope and SS probe to achieve3.2 ps resolution. The next step is the development of control system and further improvements on connection of SS probe with embedded system to boost theperformance.

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