Left-handed Transmission Line Mass Flow Meter for Particulate Solids in Pipelines

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ABSTRACT

A particulates mass flow meter has been developed using a composite right/left-handed transmission line resonator. The presented sensor principle promises the possibility to design precise particulate solids mass flow meter with moderate costs. The spatial filtering velocimetry function is applied to the CRLH-resonator in order to detect the velocity information and the material density from a single measurement. The application areas of these sensors are gas/solids, gas/liquid and liquid/solids flows in various industrial monitoring applications.

I. INTRODUCTION

The accurate mass flow measurement of particulate solids or liquids in pipelines using microwave methods is a recent field of research [1]. Besides mechanical-, acoustic- and electrostatic sensors, also microwave techniques are used for this field of application [2]-[7]. Radar systems, where a pulse or a Continuous Wave-radar signal is radiated perpendicular to the material flow into the measurement section are promising microwave techniques. Drawbacks of these techniques are moderate detection accuracy and relatively high costs of such radar systems. Other microwave systems use TM- and TE- modes inside the metallic pipeline to detect the dielectric load within the tube [3]-[6]. These techniques offer high detection accuracies for the material density but, up to now, no velocity information. The operating frequency of these systems has to be in the order of the pipelines-cutoff frequency or higher. A new sensor concept, consisting of <u>C</u>omposite <u>R</u>ight/<u>L</u>eft-<u>H</u>anded-<u>T</u>ransmission <u>L</u>ine (CRLH-TL) resonator reduces the necessary operating frequency and sensor length. In this concept series capacitors and shunt inductors are used with simultaneously negative permeability and permittivity - the so called left-handed metamaterials, that have been demonstrated superior properties [8], [9] for several applications. This paper investigates an application of this concept for a compact mass flow sensor with increased sensitivity compared to a conventional microwave mass flow sensor. A prototype of a particulate mass flow sensor for a pneumatic conveying system [10] was built up and measurements were done to proof the concept.

II. SENSOR OVERVIEW

The sensor setup consists of the signal detection (Part A), that detects the particulate flow in the pipeline, the material concentration detection (Part B) and the velocity detection (Part C). Fig. 1 displays the block diagram of the complete sensor system. The signal detection (Part A) is presented in section III. Here, the RF-signal, generated by the RF-power source is splitted by a power divider into two signals, one connected to the CRLH-TL-resonator and one connected to a phase shifter. The RF-signal obtained from the CRLH-TL-resonator is connected to one port of the phase comparator and the output of the phase shifter to the other one. If no particulate solids are fed, the setup can be calibrated to a zero phase shift $\Delta\varphi$ between both comparator signals. For a particulate flow in the pipeline, it will change and the phase comparator exhibits the phase difference versus time $\varphi(t)$. For a particulate flow in the pipeline a non zero phase shift occurs. The phase comparator gives the phase difference versus time $\varphi(t)$. The mean value of $\varphi(t)$ contains the material concentration information. Section IV explains the material density extraction algorithm (Part B). After high pass filtering (Part C), $\varphi(t)$ contains the velocity information of the material flow. The velocity extraction algorithm is presented in section V. In order to extract the velocity information the spatial filtering velocimetry method is applied to the standing waves in the measurement section.
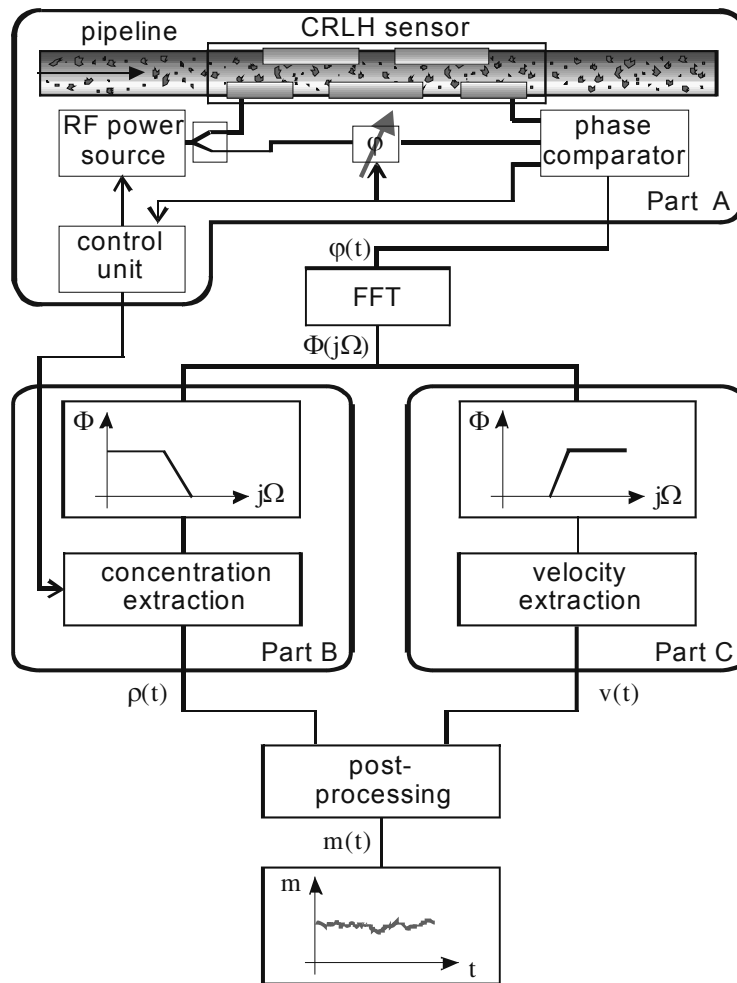
Fig. 1. Block-diagram of the complete sensor setup.

III. COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE RESONATORS
A. CRLH-TL-SENSOR DESIGN

A well known way to detect the permittivity of a solid material is to use a resonant circuit consisting of a capacitor and an inductor. A change in the permittivity of the capacitor causes a change in its capacitance and hence a shift of the circuit resonant frequency. The proposed mass flow sensor principle uses resonant circuits based on CRLH-transmission lines.

A lossless CRLH-TL can be described by its equivalent circuit (shown in Fig. 2). $L_{RH/LH}$ and $C_{RH/LH}$ represent the inductance and capacitance times unit lenght and per unit length Δz, respectively.
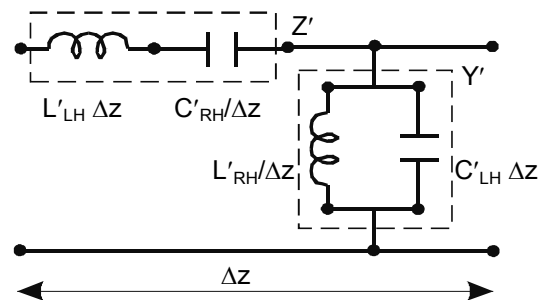

Fig. 2. Equivalent circuit model for an infinitesimal short lossless CRLH-TL.

The propagation constant for the CRLH-TL is given by

$$\gamma = \alpha + j\beta = \sqrt{Z'Y'}\,, \qquad (1)$$

where Z' and Y' are the impedance and admittance of the TL and they are defined as

$$Y'(j\omega) = j\left(\omega L'_{RH} - \frac{1}{\omega C'_{LH}}\right),$$

$$Z'(j\omega) = j\left(\omega C'_{RH} - \frac{1}{\omega L'_{LH}}\right).$$

(2)

The phase constant, or dispersion relation $\beta(j\omega)$ is

$$\beta(j\omega) = \pm\sqrt{\omega^2 L'_{RH} C'_{RH} + \frac{1}{\omega^2 L'_{LH} C'_{LH}} - \left(\frac{L'_{RH}}{L'_{LH}} + \frac{C'_{RH}}{C'_{LH}}\right)},$$

(3)

where $\beta(j\omega)$ is a real value for the RH-passband ($\beta > 0$) and the LH-passband ($\beta < 0$). β becomes imaginary outside the two pass-bands and therefore stop-bands occur. An unbalanced CRLH-TL resonator design where higher order modes are considered and $Z_{0,LH}$ is much larger than $Z_{0,RH}$, allows the design of sensitive permittivity sensors if the absolute changes of the detected permittivity are small [6].

For a constant measurement frequency the phase shift as a function of the permittivity change can be approximated by

$$\Delta\varphi = \frac{\pi}{2}\cdot Q\cdot\frac{\Delta\varepsilon_r}{2} \quad \text{for } \Delta\varepsilon_r/\varepsilon_{r,ref} \ll 1,$$

(4)

where Q is the loaded Q-factor of the resonant circuit and $\Delta\varepsilon r$ is the difference $\varepsilon_{r,meas} - \varepsilon_{r,ref}$. A system sensitivity s can be defined as

$$s = \frac{\Delta\varphi}{\Delta\varepsilon_r} = Q\cdot\frac{\pi}{4}.$$

(5)

B. CRLH-SENSOR PROTOTYPE

The cross section of the cylindrical measurement setup of the LC-loaded CRLH-TL (based on a LC-loaded microstrip CRLH-TL principle [10]) is shown in Fig. 3a.

The material density CRLH-sensor consists of a dielectric conveying tube with an inner diameter di, Metal Insulate Metal (MIM) capacitances C_{LH} assembled around the tube and wire L_{LH} from the capacitor plates to ground. The C_{RH} takes place from the C_{LH} plates to the ground layer and the LRH from the C_{LH} plates. The ground layer is a metallic tube with the diameter do. The schematic cross section of one MIM C_{LH} is shown in Fig. 3b.
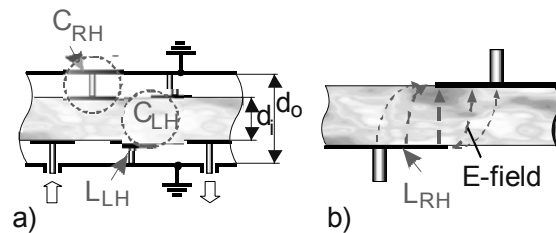

Fig. 3. CRLH-sensor: Schematic cross section of a microstrip line resonator assembled around a dielectric conveying tube (a) and cut out of a MIM capacitor (b).

The lumped element values were determined by a deembeding procedure using a circuit simulator and prove the concept of the CRLH-TL-sensor as shown in Fig 4a.
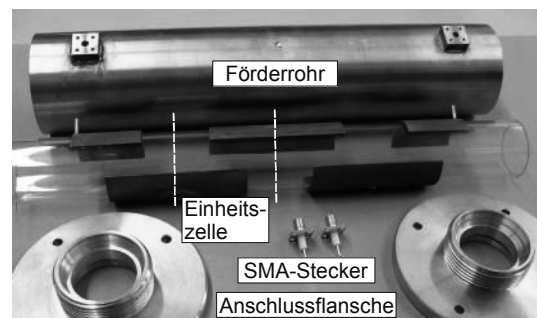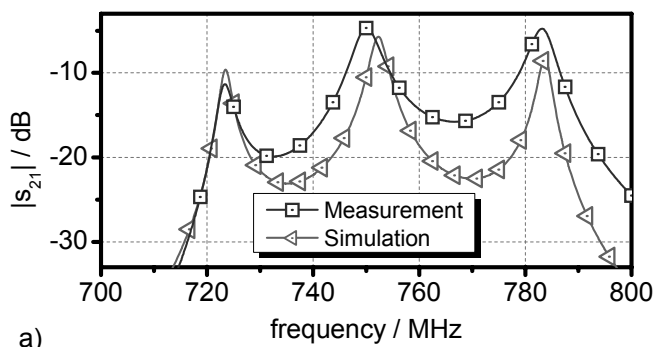

a)

b)

Fig. 4. a) Measurement results compared with circuit simulator results and b) Picture of the disassembled CRLH-sensor.

Fig. 4b shows a picture of the disassembled CRLH-sensor. The pipeline section consists of low-loss duran glass with an inner diameter of 32 mm. MIM LH-capacitors assembled around the tube and wire LH-inductors from the capacitor plates to ground. Stray RH-capacitances exist from the LH-capacitor

plates to the ground layer and stray RH-inductances along the LH-capacitor plates. The ground layer is an outer conducting tube with a diameter of 60 mm.

C. MATERIAL CONCENTRATION EXTRACTION

A change in the permittivity of the material, or the material density of the particulate solids feeded through the measurement section causes a change in the C_{LH} capacitances and hence a shift of the circuits resonant frequency. Close to the resonant frequency the phase gradient reaches its maximum and remains constant so that the resonance shift is proportional to the sensors phase shift. The material density is a function of the mean value of the detected phase shift $\varphi_{meas}(t)$. The mean value can either be taken from the integration of $\varphi_{meas}(t)$ or from the zero value of the Fourier Transform of $\varphi_{meas}(t)$. Together with the unloaded phase shift $\varphi_0(t)$ and the loaded Q-factor of the empty measurement section, the effective absolute permittivity can be approximated by

$$\varepsilon'_{r,eff}(t) \approx \left(1 - \frac{\varphi_0 - \varphi_{meas}(t)}{Q_L}\right)^2 \qquad (6)$$

The concentration α of the solids (in the solid/air mixture) in the measurement section can be defined as:

$$\alpha = \frac{V_{MUT}}{V_{Air} + V_{MUT}} \qquad (7)$$

With the assumption that $\varepsilon_{r,eff}$ is a linear function of the solids concentration, follows

$$\varepsilon'_{r,eff} = \varepsilon'_{r,MUT} \cdot \alpha + \varepsilon'_{r,Air} \cdot (1 - \alpha) \qquad (8)$$

If the specific density of the bulk material MUT is known, the integral value of the material concentration can be calculated by

$$\rho_{eff}(t) \approx \rho_{MUT} \cdot \frac{\varepsilon'_{r,eff}(t) - \varepsilon'_{r,Air}}{\varepsilon'_{r,MUT} - \varepsilon'_{r,eff}(t)}, \qquad (9)$$

where $\varepsilon_{r,MUT}$ is the permittivity of the bulk material and $\varepsilon_{r,Air}$ is the permittivity of the conveyed air (usually 1).

D. VELOCITY DETECTION

Most mass flow sensors for particulate solids, use mechanical velocity sensors, correlation- or Doppler-techniques. For conveyed powders, correlation based sensors as well as mechanical sensors are often not suitable to extract the velocity information precisely. To detect the velocity of such small particle sizes, the laser Doppler velocimetry method can be used. This technique has an extensive setup and needs two coherent lasers for velocity detection. The spatial-filtering velocimetry [9] adopts the principle of the laser Doppler velocimetry technique. The measurement setup consists of one light source and a spatial filter only.

Fig. 5a displays two examples for transmittance functions of illuminated spatial filters with grating lines for velocity measurements in the x-direction.

The light intensity I, received by a photo detector, varies periodically due to object shadowing. The obtained signal depends on the velocity of the moving object and the properties of the spatial filter. For a rectangular transmittance the output signal is a rectangular function as shown on Fig. 5a. A sinusoidal transmittance results in a periodic output signal with a sinusoidal behavior (Fig. 5b).
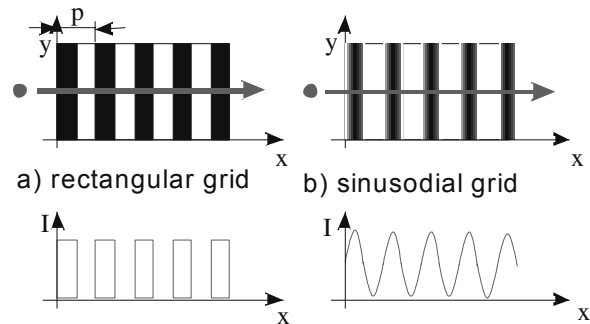

a) rectangular grid   b) sinusodial grid

Fig. 5. Spatial-filtering velocimetry: Rectangular type transmission grating with a) rectangular- and b) sinusoidal transmittance.

E. Implementation of spatial-filtering velocimetry in the microstrip patch detector

In order to extract the velocity of the objects or pulverized solids flowing through the microstrip patch sensor, the change of the complex transmission $S_{21}(t)$ at a resonant mode was investigated and the spatial filtering velocimetry was applied [10].

If a single particle passes the measurement section, the time dependent phase shift describes three sinusoidal half waves. The time difference between two adjacent phase minima corresponds to the time t, which the particle needs to travel from one field maximum to the adjacent field minimum or vice versa.

The particle position in the sensors cross section defines the maximum phase deviation at the electrical field maxima. If the particle passes the sensor in the middle of the cross section, the phase shift is larger than for the case when the particle passes the section at the outermost position of the pipelines cross-section.

IV. MEASUREMENT SETUP
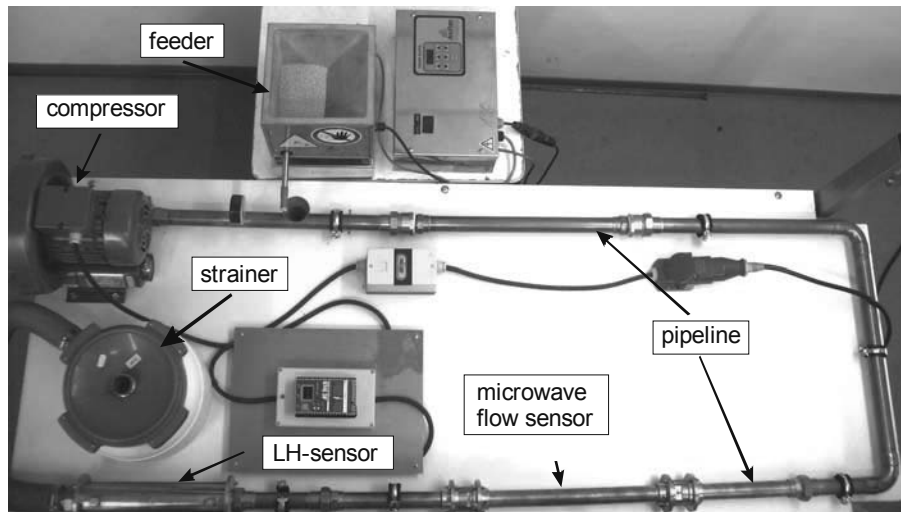The realized test facility to analyze the mass flow sensor is shown in Fig. 6.

Fig. 6. Material flow test facility: Feed rates up to 1000 g/h and velocities

It consists of a compressor, a venturi injector, a pipeline section and a strainer. The compressed air having a velocity of up to 25 m/s reaches the venturi injector, where the material is fed into the pipeline by a loss in weight feeder. The material-air mixture is nearly homogeneously distributed when it reaches the sensor. After traveling through the sensor the mixture reaches the strainer, where the material is separated from the air.

V. MEASUREMENT RESULTS
As a proof-of-concept, measurements were carried out with the material flow test. Fig. 7 shows the results obtained from feeding material with a feed rate of 1100 g/h.
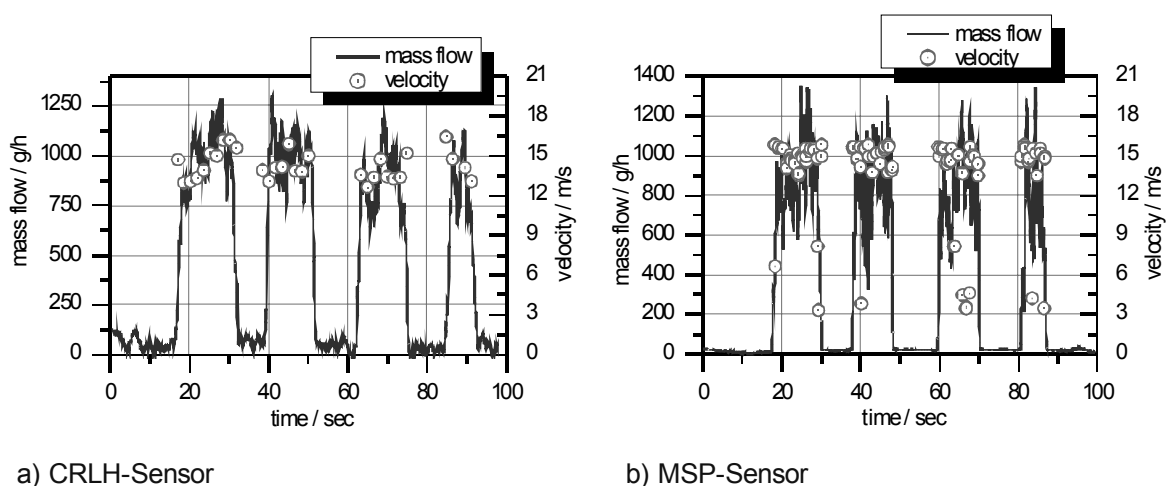
a) CRLH-Sensor   b) MSP-Sensor

Fig 7. a) Measurement results MSP-Sensor and b) Measurement results CRLH-Sensor.

The material density detected by the CRLH-sensor is shown in Fig. 7a. As expected, the detected particulate velocity is in the range of 15 m/s. The extracted mass flow rate diverges less than 10% from the original value of the loss in the weight feeder. Reference measurements were carried out with a

Microstrip Patch sensor (MSP) [10]. Up to now only measurements with a constant feedrate of 1100 g/h were carried out with a particulate velocity of 15 m/s. Two vector network analyzers were used to detect the signals for the MSP-sensor and the CRLH-sensor. Since the network analyzers were only able to detect samples in CW-mode for about 100s no long term measurements could be made up to now. The material density detected by the MSP-sensor is shown in Fig. 7b, where it can be seen that the feedrate was not constant and changes in the concentration of more than 10% were obtained. The velocity detected by the MSP-sensor differ less than ±5% from the nominal value. The results obtained for the CRLH-sensor are shown in Fig. 10. Since the averaging of the concentration detection was higher, a more smoother curve was obtained. For the CRLH-sensor a smoother curve was obtain due to the averaging in the concentration detection. The results differ less that 5% from the concentration obtained with the MSP-sensor. The detected velocity differ more that 10% from the original value.

VI. CONCLUSION & OUTLOOK

A new mass flow density sensor for process monitoring applications based on a Composite Right/Left-Handed transmission line resonator was presented. Compared to microwave sensors [3], [7] that use frequencies in the order of the pipelines cutoff frequency the CRLH-TL sensor principle can be designed for lower frequencies. There is always a trade-off between the maximum possible sensor length, the operation frequency, the sensitivity and the costs of such a system. Increasing the sensor length causes mechanical instabilities as well as a reduction of the spatial resolution, whereas increasing the frequency results in higher costs of the sensor system. The CRLH-TL resonator meets the requirements of a short sensor length, low frequencies to reduce the sensor costs and an adequate sensitivity to detect small changes in the permittivity. The spatial filtering velocimetry offers the possibility to detect the material velocity from a single sensor if its field distribution is known. The accuracy of the velocity measurements is determined substantially by the ability of the signal processing system employed.

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