Cross-sectional Detection of Flow Inhomogeneities for Pneumatic Conveyed Pulverized Solids using a Helix-shaped CRLH-Mass Flow Sensor

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ABSTRACT
This paper presents an application of Composite Right/Left-Handed (CRLH) Transmission Line resonators for compact mass flow detectors with increased sensitivity compared to conventional microwave mass flow detectors. In this concept series capacitors and shunt inductors are used to synthesize a medium with simultaneously negative permeability and permittivity - the so called metamaterial. The simultaneous detection of the velocity and the solids/air concentration from a single measurement, ensures a true mass flow detector. The helix shape of the cylindrical CRLH-TL sensor offers the possibility to detect flow inhomogeneities within the pipeline that can be applied to increase the accuracy of the detector. The rearrangement of two CRLH-TL resonators can reduce the necesasary sensorlength of the sensor and at the same time increase the sensitivity of irregularities in homogeneous distributed flows.
Prototypes of both sensor structures were realized and tested in a dedicated measurement setup to prove the concept. The application areas of this sensor are gas/solids, gas/liquid and liquid/solids flows in various industrial monitoring applications.

I. INTRODUCTION

The accurate detection of pneumatically fed solids or liquids is often a challenging task in industrial processes. Operators of combustion plants that use fossil or biological fuels such as operators of power plants, cement or steel producers are under intense pressure to improve productivity and reduce costs and environmental impact of their systems. The need of robust mass flow sensors is not only limited to large scale industries. They are also essential for many applications such as agricultural engineering where robust sensors are needed which can detect the amount and the quality of agricultural commodities directly during the harvesting processes. Several sensing principles such as mechanical, acoustic, optical, electrostatic or microwave sensors found to be suitable to detect a wide variety of materials [1]. While mechanical massflow sensors dominate in several application fields the need of the reduction of the sensors maintenance effort and at the same time the decrease of the costs for electrostatic and microwave sensors tends to a growing market for sensors based on electromagnetism principles. This paper shows a suitable sensor concept that uses microwave signals for the mass flow detection of pneumatic conveyed pulverized solids. Microwave based detection concepts usually detect the change of a electromagnetic signal guided in a metallic pipeline [2-4]. With this technique, high detection accuracies for solids concentration and velocities could be observed. The drawback of such systems is the operating frequency, that always needs to be higher than a certain frequency, the pipelines cutoff frequency. A novel sensor concept, first presented in [5], consisting of a Composite Right/Left-Handed Transmission Line (CRLH-TL) resonator can reduce the necessary operating frequency without a significant decrease of the sensors accuracy. This concept combines series capacitors and shunt inductors to synthesize a medium with simultaneously negative permeability and permittivity - the so called metamaterial [6], [7]. The conventional CRLH-TL Sensor is able to detect the mass concentration and the velocity of the particles trough a conveying tube, but up to now, it assumes uniformly distributed flows [8]. If inhomogeneities occur, this device is not able to detect them and correct the obtained measurement results. Solutions based on Electric Capacitance Tomography (ECT) for the detection of flow distribution in the tube cross-section are proposed in [1]. They are able to detect flow inhomogeneities, but they are being followed by other drawbacks like price, reliability, maintenance costs. The challenge of detecting inhomogeneous flows can either be solved by a helix shaped CRLH-TL structure [9] or by using several CRLH-TL structures assembled around the tube. The combination of two CRHL-TL structures can dramatically improve the angular sensitivity of the sensor system without increasing the sensor length [10]. Since the cross-sectional detection accuracy is a function of the number of patches assembled around the pipeline in a certain fraction of a pipeline, the accuracy can be increased by using more than one CRLH-Transmission Line distributed around the pipeline.

II. SENSOR OVERVIEW

The sensor setup consists of the CRLH-TL sensor (Part A), that detects the particulate flow in the pipeline, the material concentration detector (Part B) and the velocity detector (Part C). Fig. 1 displays the block diagram of the CRLH mass flow detector.

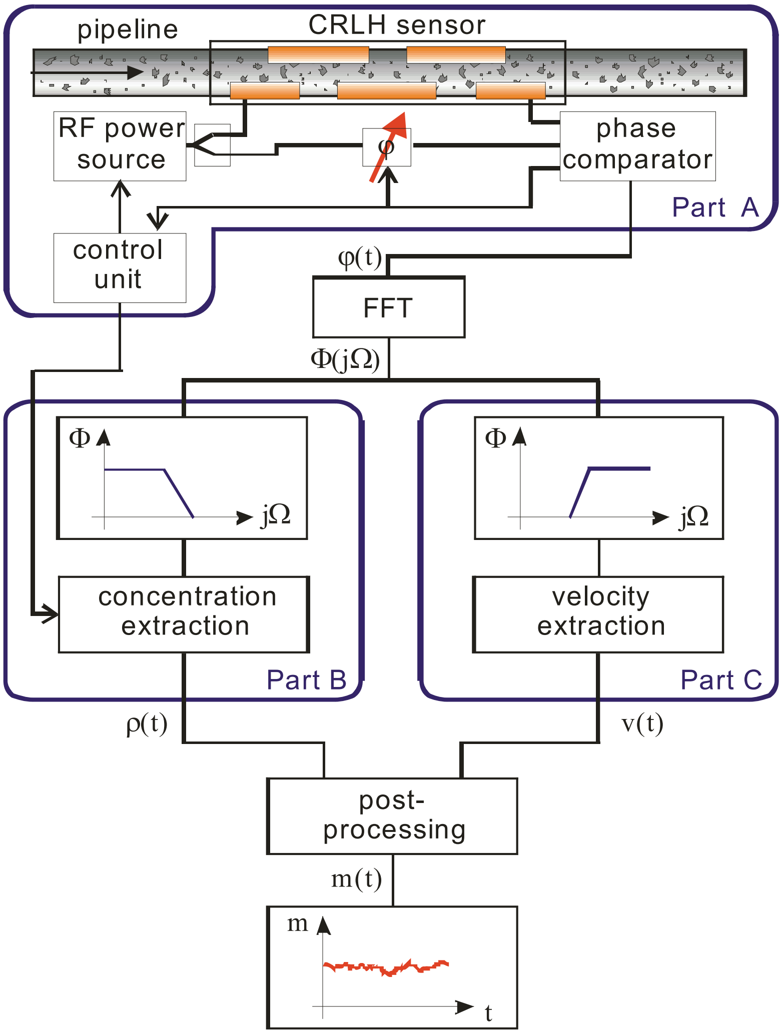

Fig. 1: Block-diagram of the complete sensor setup. Detection of differential phase vs. time (part a), material concentration (part b) and velocity and cross-sectional distribution (part c).

Part A illustrates the CRLH sensor setup. Here, the RF signal, generated by the RF power source, is split by a power divider into two signals, one connected to the sensor and the other to a phase shifter. The phase comparator gives the phase difference between the RF signal obtained from the sensors and the phase shifters output. If no particulate solids are fed, the setup can be calibrated via the phase shifter to a zero phase shift $\Delta\phi_0$ between both comparator signals. Part B explains the solids concentration extraction algorithm. The solids concentration is a function of the frequency shift and the remaining average phase shift of the detected RF signal. The Fourier Transform of the phase shift is necessary to apply the velocity detection algorithm. After high pass filtering, $\phi(t)$ contains the velocity information of the particulate solids flow. Part C describes the Spatial Filtering Velocimetry (SFV) algorithm to extract the particle velocity from standing waves in a resonant cavity [11].

III. COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE 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-TLs, a subclass of metamaterials. Metamaterials are periodic structures that exhibit homogeneous material properties as long as their periodicity, the so called unit cell, is well below the wavelength of the observing wave.

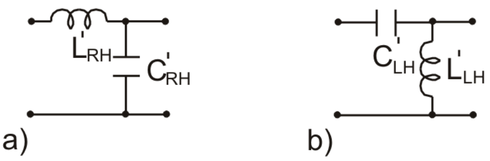

Fig. 2 Equivalent circuit model for infinitesimal short lossless RH-TL (a) and LH-TL(b).

A lossless Right-Handed (RH)-TL can be described by its equivalent circuit shown in Fig. 2a). Fig. 2b) shows the equivalent circuit for a lossless Left-Handed (LH)-TL unit cell, where $L_{RH/LH}$ and $C_{RH/LH}$ represent the inductance and capacitance per unit length for the RH case and per times-unit length for the LH case.

The propagation constant for a RH-TL and a LH-TL is given by

$$\gamma_{RH} = j\omega\sqrt{L'_{RH}C'_{RH}} \qquad \gamma_{LH} = -\frac{j}{\omega}\sqrt{\frac{1}{L'_{LH}C'_{LH}}} \tag{1}$$

In real applications a completely LH-TL is not possible, since parasitic effects always leads to a CRLH-TL. A lossless CRLH-TL can be described by its equivalent circuit as shown in Fig. 3. The wave number of a CRLH-TL can be written by

$$\beta_{CRLH} = \omega \cdot \sqrt{L_{RH}C_{RH}} - \frac{1}{\omega \cdot \sqrt{L_{LH}C_{LH}}} \tag{2}$$

L_{RH} and C_{RH} represent the distributed capacitances and inductances of a conventional TL (RH-passband). The second term in (2) accounts for a periodical reactive loading of the transmission line with lumped inductors L_{LH} and capacitors C_{LH} (LH-passband). A loose coupled TL becomes resonant for $\beta_{CRLH} = (2n+1) \cdot \pi/2$, where n is the order of the resonant mode. The CRLH TL becomes resonant for

$$\omega_{RH} = (2n+1) \cdot \frac{\pi}{2} \cdot \frac{1}{\sqrt{L_{RH}C_{RH}} \cdot \ell} \tag{3}$$

$$\omega_{LH} = \frac{\ell}{(2n+1) \cdot \frac{\pi}{2} \cdot \sqrt{L_{LH}C_{LH}}} \tag{4}$$

where $\omega_{RH/LH}$ are the angular resonance frequencies in the right/left-handed passbands. Since the Q-factor is proportional to the resonant mode, a maximum sensitivity can be achieved by the use of higher order resonant modes. For a conventional RH-TL resonator that operates in the right-handed passband, higher order modes can be achieved by an increased resonant frequency as well as increasing the length of the line. It is important to note that while a conventional resonator resonates in only positive-order (m = 1, 2, 3) modes, the CRLH resonator can resonate in negative (m = -1, -2, -3) and positive-order (m= 1, 2, 3) modes. In the left-handed passband the higher order modes result in lower frequencies. For proper chosen values for L_{LH} and C_{LH} and a fixed frequency the sensor length of the LH-TL resonator can be shortened compared to the RH-TL resonator. When the sensor length is fixed, the CRLH sensor approach reduces the necessary frequency and at the same time the sensitivity increases. The principle setup of a LC-loaded microstrip CRLH-TL is shown in Fig. 3.

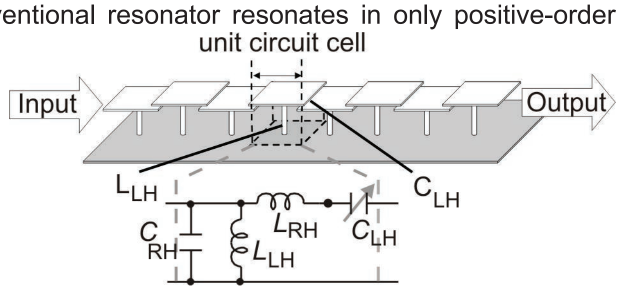

Fig. 3:Schematic drawing and equivalent unit circuit cell of a CRLH microstrip line.

The LH-inductances are realized by wires and the LH-capacitors by Metal Insulator Metal (MIM) sections along the microstrip line. Stray RH-capacitances exists from the microstrip line to the ground layer and stray RH-inductances. To use this concept for analyzing the permittivity of unknown material samples, the isolation layer of the MIM capacitors has to be exchanged by these material samples. The cross section of the modified structure of a line resonator based on this approach is shown in Fig. 4 along the microstrip line sections.

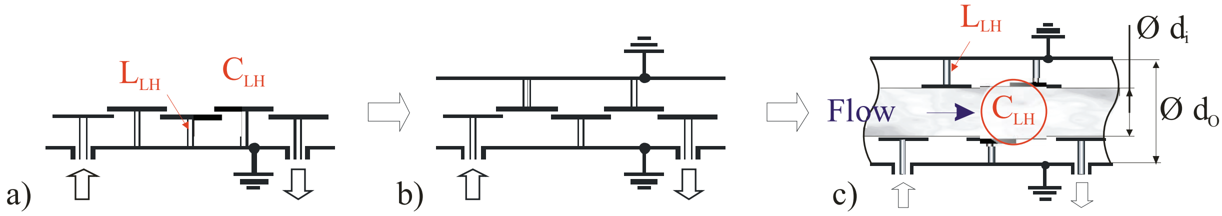

Fig. 4: a) Planar “Mushroom” structure, b) intermediate step and c) cylindrical arranged CRLH-TL sensor.

IV. HELIX SHAPED CRLH-TL SENSOR

In order to detect the cross-sectional flow distribution, the CRLH-TL sensor has a helix shape as shown in Fig. 5. The capacitance $C_{LH,n}$ of the n-th unit cell detects the material density at an angle of n times $\Delta\varphi$ of the cross-section, where $\Delta\varphi$ is the twist angle between two adjacent unit cells. Inhomogeneous flow distributions can therefore be detected by measuring the shift of the sensors resonant frequency versus time.

Fig. 6 shows the cross-sectional sensitivity maps for a small perturber at a radius of 12 mm off-center as a function of angular and longitudinal position. The plots show that the sensors resonant modes exhibit different cross-sectional sensitivities. Since all resonances are within a small bandwidth, the simultaneous detection of several resonant modes can provide information about the cross-sectional distribution profile.

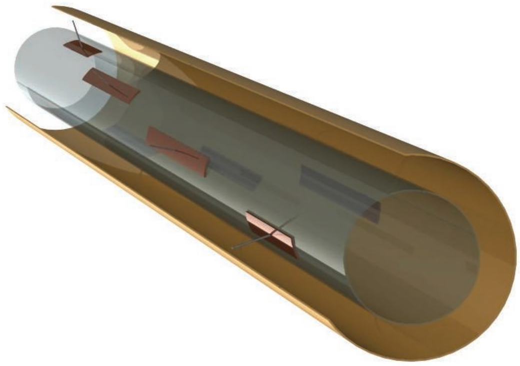

Fig. 5: Auto CAD model of the realized Helix shaped CRLH-TL sensor.

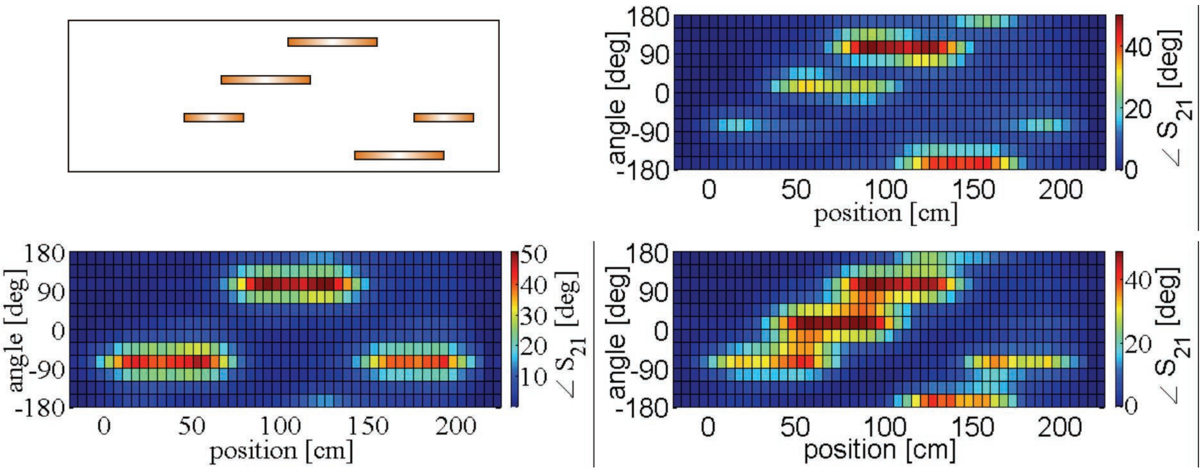

Fig. 6: Unfolded glass tube with patch positions (upper left) and sensitivity measurements of mode 1 (upper right), mode 3 (lower left) and mode 5 (lower right) for 90° twist angle.

IV. DOUBLE HELIX SHAPED CRLH SENSOR

The measurement results obtained from the single CRLH sensor displays the general functionality of this concept. To increase the cross-sectional sensitivity of the sensor, either its length can be increased and the angle between two adjacent cells reduced, or a second CRLH-TL can be radially arranged by 90 deg. to the first line so that the sensor length remains the same. Fig. 7 shows the CST model of a CRLH-TL sensor array with two helix shaped CRLH-TLs.

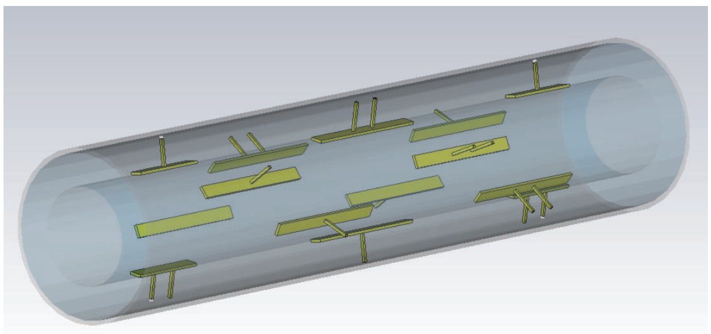

Fig. 7: CST model of the realized CRLH-TL sensor array.

If both lines work independently, the cross-sectional resolution can be increased. When using two identical lines, besides the cross-sectional distribution, also a differential signal can be obtained if both lines are fed with the same RF-signal. Fig. 8 shows the measurement setup to obtain the differential signal. If the flow is homogeneous, the combiner signal will be ideally zero since both measured signals cancel out each other. When flow-inhomo-

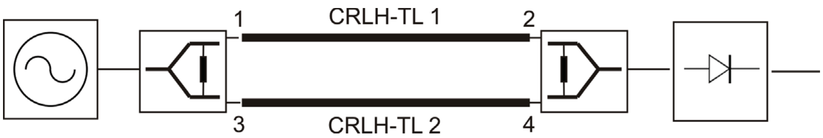

Fig. 8: Measurement setup to obtain the differential signal with two CRLH-TLs.

geneities occur, the signal will increase with respect to particle inhomogeneities in the flow profile.

Fig. 9 shows the differential signal amplitude when a particle travels in the middle and off-center inside a double line, straight arranged CRLH-TL sensor with identical CRLH-TLs. When a small particle travels off-center through the sensor, differential amplitude of ±2,5dB can be obtained, if the angular position of the perturber with respect to the CRLH-TL lines is changed from 0 deg to 360 deg. The small shift for the signal is obtained, if the perturber is in the middle of the sensor originates from the imperfections of the measurement setup. If the CRLH-TL sensor array is designed in the way, that both lines have different resonant frequencies, they can be extracted independent to each other. Fig. 8 shows the transmission of a CST simulation and measurements of a realized CRLH-TL sensor array with two CRLH-TL lines with different lefthanded inductors. It can be seen, that the first line operates at frequencies from 1.45 up to 1.65 GHz whereas the second line operates from 1.9 up to 2.15 GHz. Due to fabrication tolerances of the plates, the transmission amplitude deviates slightly between simulation and measurement. Nevertheless the resonant frequencies fit very well to the simulation results. Fig. 9 shows cross-sectional sensitivity maps measured with a perturber at a radius of 12 mm off-center in the pipeline. The plots show the influence of the sensors phase at resonance for the modes −1, −3, −5 due to the angular and longitudinal position of the perturber within the sensor. From the plots it can be seen that the mode -5 gives the best resolution. A coverage of the entire cross-section of the tube is obtained, but the differential phase shift is the lowest compared with the other modes. The detected phase shifts from the first and the second CRLH-TL are inverse, that means both lines are working independently without any mutual interference. By using the helix shaped double sensor structure, we are able to detect the flow inhomogeneities in the cross section of the tube.

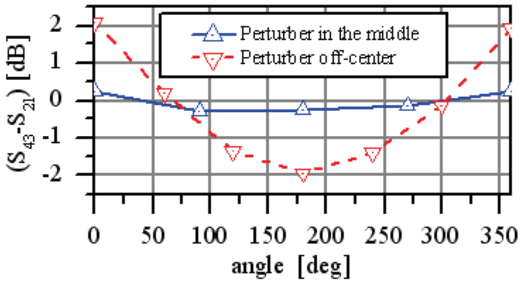

Fig. 9: Differential amplitude of the straight arranged CRLH-TL sensor.

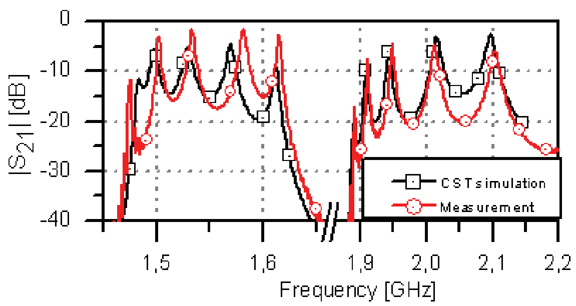

Fig. 10: Double sensor with helix shaped plates comparison: CST-simulation vs. Measurements.

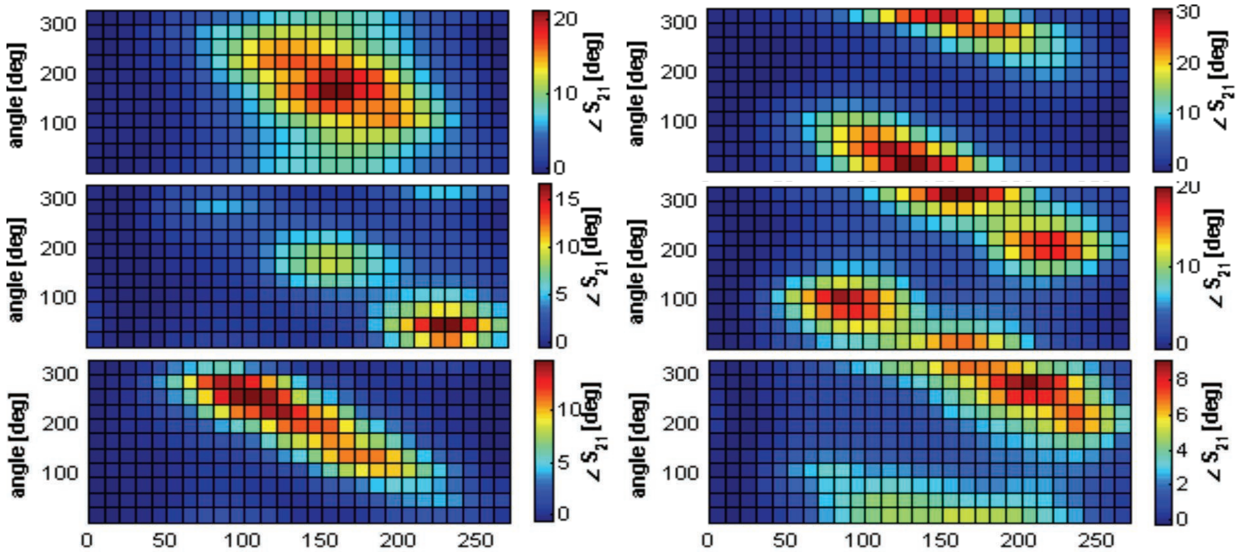

Fig. 11: Detection areas of the helix-shaped sensor with 60 twisting angle: Left line 1, right line 2 for mode 1 (upper figures), 3 and 5 (lower figures).

IV. CONCLUSION & OUTLOOK

A new mass flow detector design for process monitoring applications based on a Composite Right/ Lefthanded Transmission Line resonator-array has been realized and tested. It could be demonstrated by simulations and measurements, that with additional signal-processing the CRLH-TL sensor array with two transmission lines is able to detect the cross-sectional distribution of the flow profile in the pipeline. It could be demonstrated, that the use of multiple CRLH-transmission lines around the pipeline offers the possibility to detect the cross-sectional flow distribution of the feed material. It could be shown that besides the increase of the cross-sectional resolution, at the same time very small flow inhomogeneities can be detected when measuring the difference of the transmitted signal from both lines. The proposed Helix-shaped CRLH-mass flow detector gives promising results for the mass flow rate detection of particulate solids without disturbance of flow distribution but with a moderate to high detection accuracy compared to commercially available mass flow sensors.

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REFERENCES

[1] Y. Yan, and D. Stewart, “Guide to the Flow measurement of Particulate Solids in Pipelines”, published by the Institute of Measurement and Control, National Engineering Laboratory, and the University of Greenwich, April 2001.

[2] A. Penirschke, J. Freese, J. Biebel, B. Allenberg, and R. Jakoby, “Novel integrated coaxial line to cylindrical waveguide directive couplers in pipelines for process monitoring applications”, 2005 MTT Int. Microwave Symp. Dig., pp. 1203-1206, June 2005.

[3] A. Penirschke, and R. Jakoby, “Accurate Material Density Measurements of Particulate Solids in Pipelines with a Novel Microwave Flow Sensor”, 13. ITG/GMA Fachtagung Sensoren und Messsysteme 2006, Freiburg/Breisgau, March 2006.

[4] H. G. Conrads, “Method and device for a contact-free measurement of the mass flow rate in a two phase pneumatic transport using microwaves,” EP. Patent 0 717 269 A2, Nov. 24, 1995.

[5] A. Penirschke, M. Schüßler, and R. Jakoby, “New Microwave Flow Sensor based on a Left-Handed Transmission Line Resonators”, 2007 MTT Int. Microwave Symp. Dig, June 2007.

[6] H. Maune, M. Schüßler, A. Penirschke, C. Damm, and R. Jakoby “Left-Handed Transmission Line for Permittivity Measurements”, Metamaterials Conference 2007.

[7] C. Caloz, and T. Itoh, “Novel Microwave Devices and Structures Based on the Transmission Line Approach of Meta-Materials”, 2003 MTT-S Int. Microwave Symp. Dig., vol. 1, pp. 195-198, June 2003.

[8] A. Penirschke, and R. Jakoby, “Microwave Mass Flow Detector for Particulate Solids based on Spatial Filtering Velocimetry”, 2008 IEEE Transactions on Microwave Theory and Techniques, vol. 56, pp. 3193 - 3199, Dec. 2008.

[9] A. Penirschke, A. Angelovski, R. Jakoby, “Helix-shaped CRLH-Mass Flow Detector for the Cross-sectional Detection of inhomogeneous distributed pneumatic conveyed pulverized Solids” *accepted for publication, I2MTC conference, Hangzhou*, 2011

[10] A. Angelovski, A. Penirschke and R. Jakoby, “Helix-shaped CRLH-TL sensor for inhomogeneties detection for pneumatic conveyed pulverized solids” *accepted for publication, 6th German Microwave Conference GeMiC2011, Darmstadt*, 2011

[11] Y. Aizu, and T. Asakura, “Spatial Filtering Velocimetry”, Springer Verlag, Berlin, 2006.