Integrated Microwave Sensors for Cavity-Length Measurement in Machine Engineering

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***Abstract*—A novel measurement procedure using microwaves is presented. The implemented sensor prototype determines the length of a cylindrical cavity (e.g., a hydraulic system) with submillimeter accuracy in real time. The principle of operation is based on the detection of the resonance-frequency distribution in a cavity resonator.**

***Index Terms*—Algorithms, intelligent sensors, length measurement, mechanical variables measurement, microwave measurements, MODFET integrated circuits, position measurement, real-time systems.**

I. INTRODUCTION

MICROWAVE sensors offer a possibility to implement novel and cost-effective measurement systems for science and industrial applications. Extensive use of microwave monolithic integrated circuits allows one to enable contact-less, nondestructive, and real-time measurements.

Depending on how the measurement is arranged and which physical phenomenon is used, microwave sensors may be divided into several groups [1]. This paper deals with a measurement system that is based on the resonance principle. There has been a number of sensors employing this phenomenon (e.g., [2]–[4]).

Fig. 1 shows a schematic representation of a structure that has been used very often in the area of mechanical engineering. It consists of a metallic cylinder that is closed from one side. From the other side, a movable piston is placed into this cylinder, which is filled with a dielectric medium. As an example, a robotic arm can be considered. However, hydraulic systems of a variety of machines and different shock-absorber systems use a similar arrangement.

Due to the fact that—in the case of the measurement problem shown in Fig. 1—one has to deal with a closed cavity, there

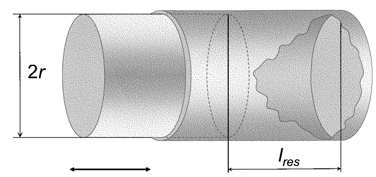

Fig. 1. Schematic description of the measurement problem.

is only a limited number of possible sensor solutions. For example, it could be a distance measurement based on inductive or capacitive distance sensing [5]. However, the measurement range is rather limited. Further potential solutions include pulse (e.g., [6]), frequency-modulated continuous-wave (FMCW) radars (e.g., [7]), and time-domain reflectometry (e.g., [8]). However, these methods can only hardly be used for the measurement of small distances within a cylinder structure due to a high complexity on the electronic side or due to a very difficult coupling.

This paper defines a measuring procedure that determines the length l_{res} of the resulting cavity without disturbing mechanical properties of the system. Furthermore, measurements can be performed several times per second. The basic idea relies on the consideration of the resonance-frequency distribution within a cavity (Section II-A). The proposed measurement principle is not limited to the cylindrical cavity shape. It can be also used to determine the length of a cavity with an arbitrary cross section.

A demonstrator for the length measurement in cylindrical cavities was manufactured (Section II-B) to prove the feasibility of the proposed sensor principle. The dimensions of the prototype have been chosen in such a way that the prototype models an automotive shock absorber. This application sets tight requirements to the system to be developed: fast operation, contact-less measurement, no special calibration, cost-effective implementation for possible mass production, temperature stability, and resistance to a hostile environment. The integrated sensor was tested, also in view of its possible use in industrial applications (Section III).

A microwave sensor delivers an output signal in any way containing information about the unknown parameter to be measured. In the case discussed in this work, the information about the cavity length is incorporated into the resonance pattern. Thus, the desired value has to be mathematically extracted from an electrical signal. In Section IV, an algorithm implementation is described, which evaluates the actual cavity length from the sensor-output signal and completes the entire measurement system.

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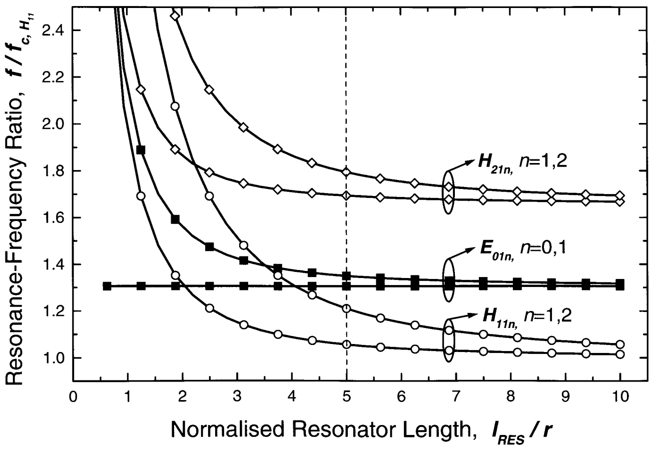


Fig. 2. First three resonance modes within a cylindrical cavity (without coupling). Higher resonance numbers n of a particular mode correspond to the resonances with higher frequencies.

II. Operation Principles and System Design

A. Measurement Procedure

The principles of the sensor operation are based on the fact that the initial mechanical structure from Fig. 1 can be considered as a cylindrical cavity resonator. The resonance frequencies in a cavity strongly differ from one mode to another. Further, they usually are a function of length for every single mode. Fig. 2 demonstrates several frequencies for the first three resonance modes of an ideal cylindrical cavity. In this figure, the resonance-frequency ratio—the normalizing factor is the cutoff frequency $f_{c,H_{11}}$ of the basis cylindrical waveguide mode—is shown as a function of the normalized length $l_{\rm res}/r$, where r is the resonator radius.

According to Fig. 2, only certain resonance frequencies correspond to a particular resonator-length value (e.g., dashed line). This resonance-frequency sample (taken from a particular frequency range) is unique for every resonator length. Therefore, if a resonance-frequency set is fixed for a particular resonator length, this length value—which is the parameter to be determined—can be unequivocally extracted.

For sensor applications, the resonance mode E_{01n} is of a special interest. It is the first mode that owns a basis resonance (E_{010}), whose frequency does not depend on the resonator length. Therefore, it can be used as a stable calibrating reference allowing one to take into account only the resonance-frequency distribution (or the position of resonances in respect to each other) and not the absolute value of resonance frequencies. This calibrating reference can be also used to measure the parameters that exhibit only a weak time dependence (e. g., the dielectric permittivity ε_r or the temperature of operation).

The advantage of the distribution technique is the independence of the measurement principle from the absolute values of resonance frequencies if a particular reference is available. For the sensor system under consideration, this requirement is fulfilled by the resonance modes with a first resonance exhibiting no dependence on the resonator length. Within a circular cylindrical cavity resonator, these modes are: $E_{01n},E_{11n},E_{21n},,\ldots$. Furthermore, using the resonance-frequency distribution, the measurement principle ideally becomes independent from the material characteristics of the dielectric medium filling the resonator. This behavior can be used for the mathematical evaluation of the sensor output.

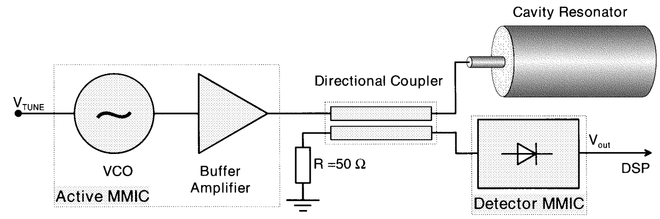


Fig. 3. Block schematic of the sensor system for cylindrical cavity-length measurement.

The following procedure can be employed to implement the measurement idea described above.

1) Choose a particular frequency range according to the dimensions of the cylinder, whose length has to be measured. The latter choice has to be done also in view of a particular resonance mode to be used (e. g. E_{01n} from Fig. 2). The stimulation of a particular resonance mode allows one easier evaluation of the actual resonator length. Further, the wider the chosen bandwidth range is the lower the minimal resolvable length becomes and the higher the sensor resolution is.
2) Within the chosen frequency range, tune the frequency from one bound to another. In this way, resonances are stimulated within the cavity resonator, which has a particular length value. These resonances appear at a certain value of a particular control variable (e.g., the tuning voltage of a signal source or time). The frequency tuning can be provided by a signal source generating a signal over the chosen frequency band.
3) Detect the appearing resonances as a function of the chosen parameter and calculate the actual resonator length from the output function.

B. Sensor-System Structure

According to the measurement procedure for the length determination of a cylindrical cavity, a sensor concept is proposed whose structure is depicted in Fig. 3.

A sinusoidal signal generated by a voltage-controlled oscillator (VCO) is amplified by a buffer amplifier and then it is applied to the cavity resonator over a simple directional coupler. The buffer amplifier reduces the influence of the variable resonator-input impedance on the VCO performance. The frequency of the microwave signal can be tuned within the chosen frequency range. In this way, the corresponding resonances of the cavity are stimulated. Here, the E_{01n} mode is used for length determination. To excite this mode only—which is a rotation-symmetric one—a specific coupling structure has to be employed.

At the resonance frequencies of the cavity, the signal power is translated into the resonator. For all other frequency values, the signal is simply reflected back to the coupler. The reflected signal is fed via the coupler to the detector circuit, which detects the power level of the reflected signal. The variation of the power level over frequency results in an alteration of the

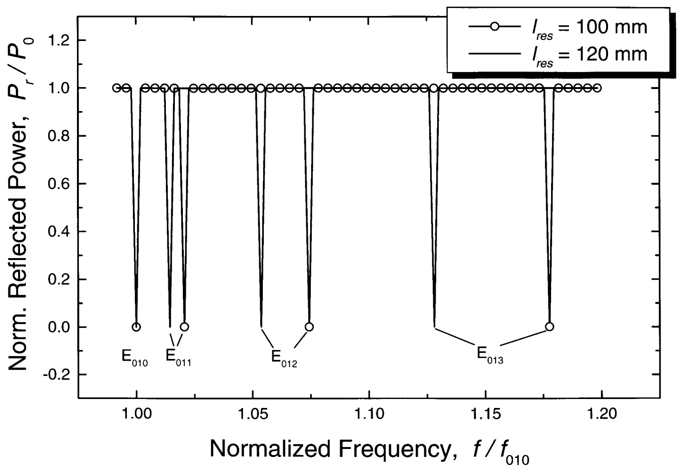


Fig. 4. Visualization of the measurement principle. Power of the signal reflected from the resonator cavity is shown as a function of the normalized frequency. The E_{01n} resonance mode is considered.

detector-output voltage. The detector output now contains the information about the distribution of the resonance frequencies within the cavity resonator. Passing this signal to the digital-signal processing (DSP) unit, the actual resonator length can be calculated using a mathematical algorithm.

Instead of recognizing a voltage drop in the plain of the electronic circuitry, the sensor measures the level of the signal power reflected from the resonator. The frequency values, at which the power dissipation exhibits its maximum, are the resonance frequencies of the resonator together with the coupling structure. Also, the behavior of the resonator including its coupling—and hence, the resonance-frequency values—can be analytically determined.

Fig. 4 visualizes the operation principle of the sensor system. It presents the normalized power level of the reflected signal at the input of the detector circuit as a function of the normalized frequency for an ideal case. The reference factors are the output power level P_0 of the signal source and the frequency of the frequency f_{010} of the E_{010} resonance.[1] The chart clearly demonstrates the relative position of the cavity resonances for two different resonator lengths. At these resonances, the value of the reflected power is zero. If the position of the resonances is correctly determined by the detector circuit, the length of the resonator can be calculated.

Generally, the proposed measurement system can be employed with a cavity having arbitrary parameters. In the case of the demonstrator described here, these variables are the dimensions of the cylinder (its radius and length range) and the art and characteristics of the filling material, which can be any gas or any dielectric liquid. These parameters alter from one application to another. Therefore, the frequency bandwidth of operation and resonator coupling have to be defined for a particular mechanical system.

In this work, a sensor system was designed, manufactured, and tested for a cavity, whose parameters are listed in Table I. The dielectric medium is the REPSOL vegetable oil. This cavity has the same characteristics as the considered automotive shock absorber. It was chosen to implement a prototype of a sensor system, which should demonstrate the feasibility of the proposed measurement principle and to investigate its performance.

TABLE I
SUMMARY OF CAVITY PARAMETERS

Dielectric Constant	ε_r	2.2
Magnetic Constant	μ_r	1.0
Resonator Radius	r/mm	16
Resonator Length	l_{res}/mm	30–200

1) Cavity Coupling Issues: Because of the basic idea behind the cavity-length measurement that is described above, only the E_{01n} resonance mode is taken into account. Moreover, the excitation of other modes such as the H_{11n} complicates the length-evaluating procedure. Therefore, the coupling of these further resonance modes should be made as small as possible. On the other hand, the coupling of the E_{01n} mode has to be strong to allow one a clear detection of single resonances. Due to the radial-symmetrical nature of the E_{01n} mode, the coupling structure has to be chosen to be radially symmetric. It is obvious that radially symmetric field probes should stimulate the modes with $\partial/\partial\varphi = 0$ only.

The proposed particular implementation of the field probe is a disc at the end of a pin that provides coupling between the resonator cavity and a coaxial waveguide. Measurements of a coupled cavity resonator by means of an HP8510 network analyzer showed that the rotation-symmetrical modes (E_{01n}, E_{02n}) are solely excited using this kind of coupling.

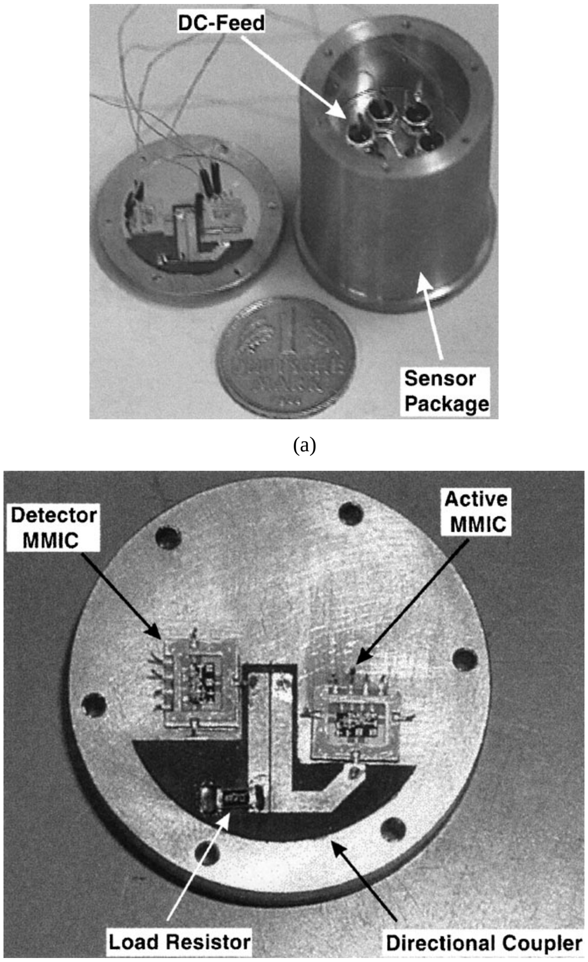
2) Electronic Part of the Sensor: As shown in Fig. 3, the electronics part of the sensor contains a VCO, a buffer amplifier, and a detector circuit. For the considered frequency range, the circuitry could be realized using either a hybrid microwave integrated circuit (MIC) or monolithic-microwave integrated-circuit (MMIC) technique. In view of the size reduction and the possible series production, the MMIC technology is a very interesting alternative. Due to the reduced circuitry size, the sensor system can be directly integrated within a cylinder. In the case of mass production, the costs per unit can also be significantly reduced.

On the other hand, the distance between single resonances becomes smaller for longer resonators (Fig. 2), which can lead to a difficult resonance separation and higher measurement error. Hence, higher resonances with $n = 4..7$ should be taken into account for higher sensor precision. This leads to the requirement that the frequency range covered by the VCO should be as wide as possible. This is a very demanding requirement for a fully monolithically integrated VCO.

The signal source employed in the current sensor implementation is a feedback MMIC-VCO described in [9]. It offers an excellent combination of bandwidth (4.6–7.2 GHz, i. e. 45%), output power ($P_{\rm out} \approx 14.1 \pm 0.7$ dBm), high tuning linearity, and temperature stability. It is manufactured using the PH25 pHEMT process of the United Monolithic Semiconductors S.A.S. (UMS).

The detector circuit considered here employs a pHEMT in common-source configuration. The RF signal, whose power-level alterations have to be detected, drives the gate–source diode of the transistor while controlling its drain

[1]The calculations were performed for the initial dimension of the resonator cavity listed in Table I.



(a)

(b)

Fig. 5. Photograph of the packaged sensor. (a) The entire system. (b) Close-up view of the active area.

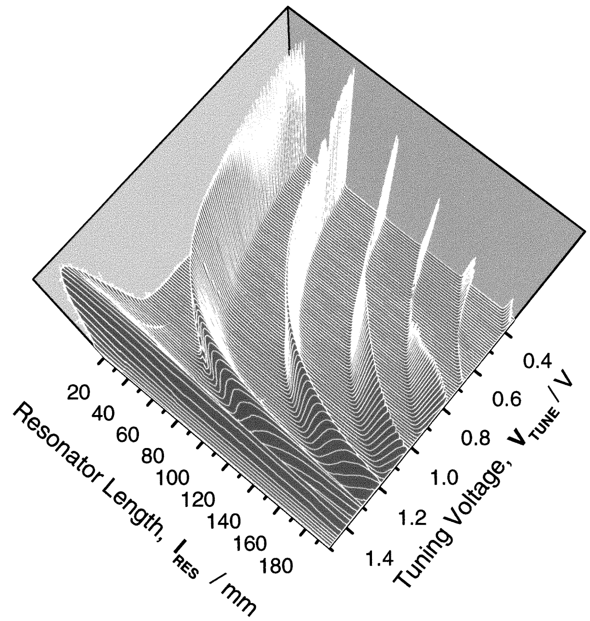


Fig. 6. Detector output voltage as a function of the VCO tuning voltage and the resonator length presented in a 3-D plot.

current. Therefore, the dc part of this current is inverted proportionally to the level of the input power.

III. Sensor-System Test and Experimental Results

A. Sensor-System Assembly

A sensor prototype was manufactured using the derived measurement procedure and the proposed sensor-system structure (Fig. 3). Fig. 5(a) and (b) shows photographs of the packaged sensor system. The packaged MMICs—the active one as well as the detector one—together with the directional coupler are glued onto a brass disc that also carries the coupling structure and provides grounding and an excellent heat sink. Due to cost reasons and for higher flexibility, the VCO and the detector are integrated on a single die. Thus, identical chips are used for "*Active MMIC*" and "*Detector MMIC*."

B. Measurement Results

The behavior of the sensor prototype was measured using a testing system employing a step motor, which allows one to drive the piston longitudinally with a minimal step of $\Delta l = 5$ μm. The tuning voltage of the VCO was provided by the dc-voltage source HP3631E and was altered in steps of $\Delta V_{\mathrm{TUNE}} = 5$ mV. The output detector voltage V_{DET} was measured by the multimeter HP4537. The entire measurement setup was controlled by the software tool LABVIEW running on a standard PC.

Fig. 6 shows the obtained values of the detector-output voltages as a function of the tuning voltage and the resonator length $V_{\mathrm{det}} = f(V_{\mathrm{TUNE},} l_{\mathrm{res}})$. In this three-dimensional (3-D) plot, one can recognize that the E_{01n} resonance mode of the cylindrical structure was detected only and the distribution of the resonance frequencies corresponds to the theoretical behavior of the E_{01n} mode in a cylindrical resonator cavity.

Furthermore, all of these resonances (maxima of V_{det}) were detected. A comparison with the results of the resonator characterization by means of the network analysis showed that all resonances could be also recognized correctly.

Analyzing Figs. 2 and 6, one can see that the resonance-frequency gradient with respect to the resonator length decreases with increasing values of l_{res}. This behavior implies that the minimal detectable resonator-length alteration is to look for at higher length values for the case that the next-higher resonance frequency is not detectable yet. For the considered frequency-tuning and resonator-length ranges, this "critical" length was determined to be as high as $l_{\mathrm{res}} = 189$ mm. Fig. 7 demonstrates the detector output for value of the resonator length of $l_{\mathrm{res}} = 189$ and 189.5 mm. The inset within this figure shows that this small length difference is resolvable with the sensor. Assuming that this change is also applicable and detectable by a computer using a certain algorithm, the length resolution of the sensor system would be under $\Delta l = 1$ mm.

Performing dynamic measurements, almost no variations of the detector-output voltage were found up to 100 tuning-voltage sweeps per second. Above this frequency, the position of the resonance peaks as well as their heights start to change.

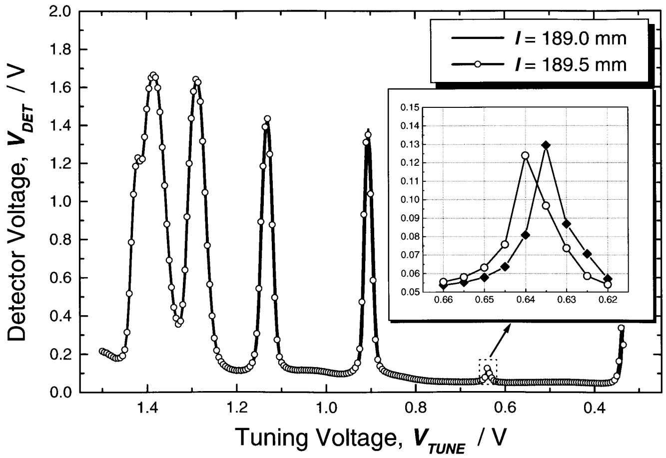


Fig. 7. Detector output voltage as a function of tuning voltage at the resonator-length values of $l_{\rm res} = 189.0$ and 189.5 mm.

IV. Evaluating Algorithm

The mathematical algorithm has to accomplish the task of the actual resonator-length extraction from the measured detector-output voltage array. It mainly determines the accuracy and the resolution of the sensor system implemented.

This section represents an implementation of the evaluating procedure. The approach employs the cross-correlation technique. The idea behind this is based on the following considerations. Generally, cross correlation between two arbitrary functions $x(t)$ and $y(t)$ is defined as follows:

$$R_{xy}(\tau) = \int_{-\infty}^{+\infty} x(t) \cdot y(t-\tau) dt \tag{1}$$

This function exhibits a maximum for a value of τ, at which the functions $x(t)$ and $y(t)$ are most "similar" to each other. Thus, if a correlation function could be defined that unequivocally corresponds to a particular resonator length, its cross correlation with the detector output should help to extract the actual resonator length.

A. Formal Description of the Algorithm

The detector output is an experimental measure and acts as an input for the algorithm under development. It is a function of the tuning voltage and, at the same time, it changes with the unknown resonator length as clearly demonstrated in Fig. 6. Therefore, the correlation function demanded—called Y here—also has to be a function of the same two variables. In the further course of this section, a function $Y(l_{\rm res,} V_{\rm TUNE})$ is introduced that is employed within the evaluating algorithm.

Consider the expression for the resonance-frequency distribution of the E_{01n}-mode within an ideal cylindrical cavity resonator

$$f_{01n} = \frac{1}{2\pi} \cdot \frac{c_0}{\sqrt{\varepsilon_r \mu_r}} \cdot \sqrt{\left(\frac{j_{01}}{r}\right)^2 + \left(\frac{n \cdot \pi}{l_{\rm res}}\right)^2}. \tag{2}$$

In the above equation, c_0 is the light velocity in vacuum. The parameter ε_r is the permittivity of the dielectric material and μ_r is its magnetic constant. The zero of the Bessel's function that corresponds to the considered mode is $j_{01} = 2.405$. Using the definitions

$$f_0 := \frac{c_0 \cdot j_{01}}{2\pi \cdot r \cdot \sqrt{\varepsilon_r \mu_r}} \text{ and } C := \pi^2 \left(\frac{r}{j_{01}}\right)^2 \tag{3}$$

(2) can be rewritten as follows:

$$f_n := f_0 \cdot \sqrt{1 + C \cdot \left(\frac{n}{l_{\rm res}}\right)^2}, \qquad n \in \aleph_0. \tag{4}$$

The frequency dependence of the MMIC-VCO can be expressed by a linear function of the tuning voltage

$$f = a + b \cdot V_{\rm TUNE.}. \tag{5}$$

The assumption (5) is justified by the fact that the oscillation-frequency dependence on the tuning voltage is fairly linear as shown in [9].

With (2)–(5), the following relationship can be set:[2]

$$V_{\rm res}(l_{\rm res,} n) = \frac{1}{b} \cdot \left[\underbrace{(a + b \cdot V_0)}_{f_0} \cdot \sqrt{1 + C \cdot \left(\frac{n}{l_{\rm res}}\right)^2} - a \right] \tag{6}$$

where V_0 is the tuning voltage, at which the basis resonance E_{010} is detected. The above expression defines the values of the tuning voltage at which the resonances—that correspond to the resonance mode E_{01n}—should appear within the cylindrical cavity for a given resonator length $l_{\rm res.}$ The natural factor $n \in \aleph_0$ denotes different resonances belonging to the mode E_{01n}.

Now, the following function array, which should be used as the correlation function within the algorithm, can be defined:

$$Y(l_{\rm res,} V_{\rm TUNE}) \equiv \sum_{n=0}^{n=n_{\max}} \delta\left(V_{\rm res}(l_{\rm res}, n) - V_{\rm TUNE}\right) \tag{7}$$

where δ is a simple Dirac-impulse and $V_{\rm res}$ is defined by (6). For a particular resonator length, the defined function Y returns a row of Dirac-pulses at the values of the tuning voltage $V_{\rm TUNE} = V_{\rm res}$ defined in (6). At the tuning voltage $V_{\rm TUNE} \neq V_{\rm res}$, the function Y is zero. The parameter $n_{\max}$ can be easily found from the frequency range considered and the maximal resonator length to be measured.

After performing a cross-correlation calculation between the measured detector output X and the defined correlation function Y, an array of cross-correlation functions can be found. At the demanded value $l_0 = l_{\rm res}$, this function array exhibits an absolute maximum. Therefore, the determination of this maximum array delivers the value of the actual cavity-resonator length $l_{\rm res}$.

B. Determination of the Actual Cavity Length

Using the developed algorithm based on the cross-correlation technique, the resonator length was calculated from the measured

[2]In (6), the variable $V_{\rm TUNE}$ from (5) is renamed to $V_{\rm res}$ to avoid the mix-up between the *actual* VCO tuning voltage $V_{\rm TUNE}$ and the value $V_{\rm res}$ *calculated* using the ideal resonance distribution from (6).

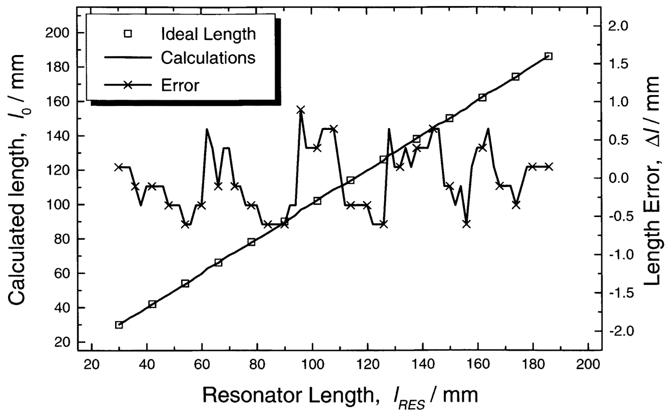


Fig. 8. Calculated length of the resonator and the length-determination error as a function of the actual length at room temperature. The algorithm procedure based on the cross-correlation technique was used for these calculations.

TABLE II
PERFORMANCE SUMMARY OF THE SENSOR SYSTEM EMPLOYING THE ALGORITHM BASED ON THE CROSS-CORRELATION TECHNIQUE

Characteristic	**Dimension**	**Value**
Minimal Length Resolvable	$l_{0,\min}$ / mm	30
Length Resolution	Δl / mm	<1
Max. Calculation Error	$\Delta l/l_{res}$ / %	1%

TABLE III
MEASURED PERFORMANCE OF THE SENSOR SYSTEM REALIZED

Minimal Length Detectable	$l_{res,\min}$ / mm	30
Length Resolution Using the Algorithm Developed	Δl / mm	< 1
Max. Calculation Error	$\Delta l/l_{res}$ / %	1%
Dynamics (Hardware Limit)	f_{sweep}/ Hz	100
Max. Operation Temperature	$T_{\max}$/ °C	100

values of the detector output at room temperature. The tuning voltage was discretisized in steps of $\Delta V = 5$ mV resulting in 241 values of $V_{\rm det}$ considered for some particular resonator length. The minimal length step was chosen to be $\Delta l_{\rm res} = 0.5$ mm within the range of $l_{\rm res} = 10$–210 mm. With this parameters, 401 length values were taken into account.

The proposed algorithmworks perfectly for the resonator length under consideration. Fig. 8 shows the obtained values l_0 as a function of the actual resonator length $l_{\rm res}$. The length-determination error $\Delta l = l_0 - l_{\rm res}$ is also presented in Fig. 8. Within the entire length range considered, resonator length were correctly determined with an accuracy of at least ± 1 mm. The same submillimeter accuracy could be achieved within the investigated temperature range of $T = 20$ °C–100 °C. Furthermore, the length difference of $\Delta l_0 = 1$ mm could be clearly resolved.

Table II summarizes the performance of the developed and manufactured integrated sensor for cavity-length measurement employing the algorithm, which is based on the cross-correlation approach. The evaluating technique not only delivers the actual cavity length, but is also able to calculate the permittivity of the filling dielectric material. Knowing its temperature dependence, the actual temperature within the structure can be also extracted.

V. CONCLUSION

This paper presents a solution for a classic problem of length measurement in closed structures by means of microwaves. The basic measurement principle is based on the detection of the resonance-frequency distribution within a cavity resonator. The proposed measurement principle can be also used to determine the length of a cavity with an arbitrary cross section.

Here, the feasibility of the proposed sensor concept has been successfully demonstrated for an example of a particular cylindrical cavity. Table III summarizes the main performance of the integrated sensor prototype for cavity-length measurement.

The proposed mathematical algorithm allows one the evaluation of the sensor output with submillimeter accuracy over a wide temperature range. Furthermore, the permittivity of the filling dielectric material can be also extracted.

The excellent combination of the measurement speed, accuracy, and length resolution of the sensor system designed and manufactured in this work makes it very interesting for various industrial applications, e.g., in automotive shock absorbers [10].

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Claus D. Hamann, photograph and biography not available at time of publication.

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