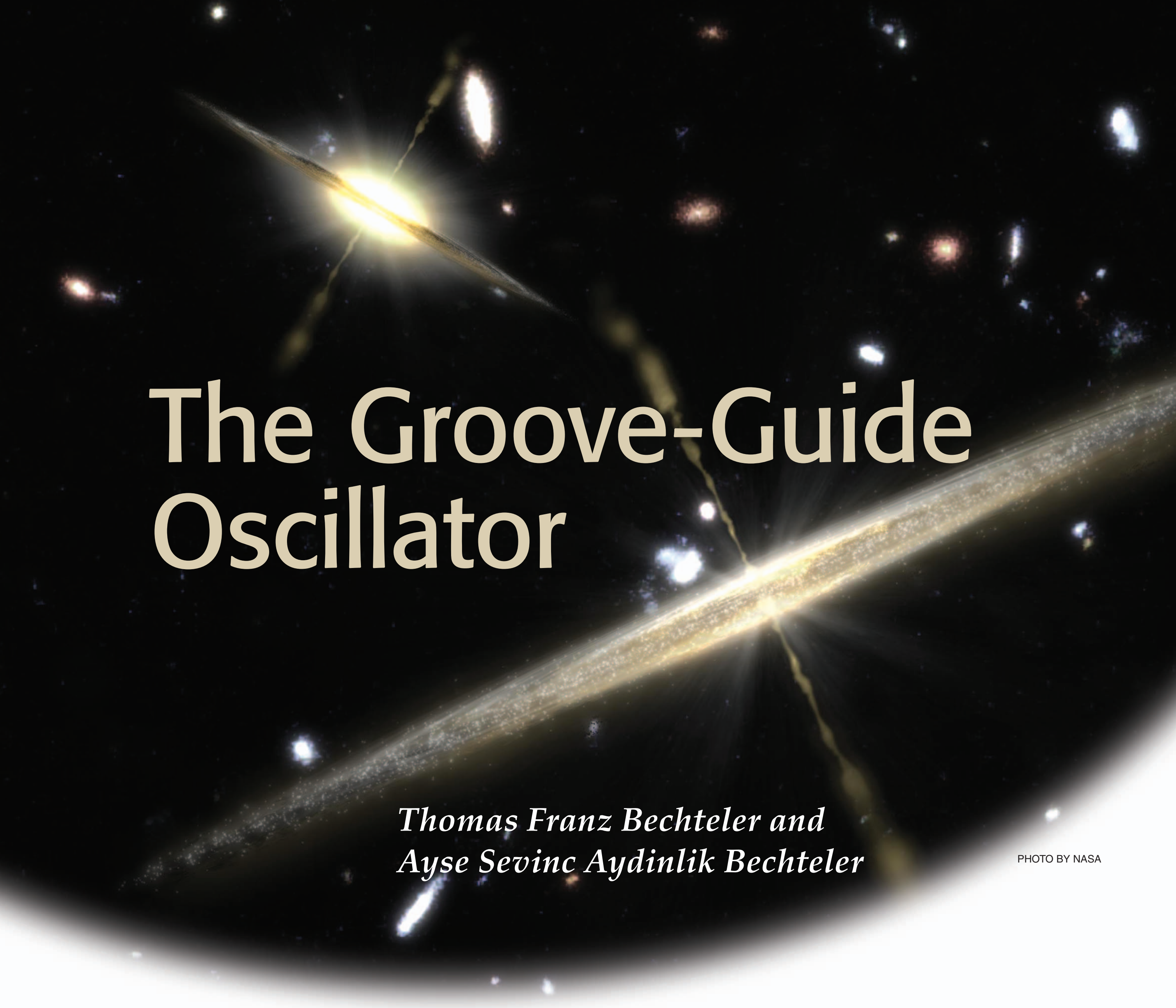

The Groove-Guide Oscillator

Thomas Franz Bechteler and Ayse Sevinc Aydinlik Bechteler

PHOTO BY NASA

The groove guide is a low-loss waveguide that was proposed by Tischer [1] in 1963 as an alternative to classic waveguides. Its basic structure, shown in Figure 1, can be divided into an inner and two outer regions. The inner region exhibits a lower phase velocity. Hence, the electromagnetic field is concentrated in the inner region and propagates along the groove. In the outer regions, the electromagnetic field is evanescent. After Tischer, many works focused on finding analytical solutions describing the electromagnetic field distribution inside the groove structure. These publications include the works of Griemsmann [2], Oliner et al. [3], and Fernyhough et al. [4]. Furthermore, different shapes of the groove's cross section were the subject of investigation in [5]–[7]. With the improvement of computer power, especially with respect to increased memory, numerical methods became popular. A widely applied method is the finite-difference time-domain (FDTD) method introduced by Yee [8] and described in the book by Taflove [9]. The groove structure has been frequently investigated using this method.

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In manufacturing the groove guide, the problem arises as to how to align the two plates with a desired standoff distance. To solve this problem, different solutions have been proposed. As illustrated in Figure 2(a), Thiébaut and Roussy [10] suggested mechanical spacers fixed with screws at the ends of the groove guide's outer regions. Thus, a plate distance *h* with good alignment is guaranteed. For the fundamental TE_{11} mode, it doesn't matter whether these spacers are made of metal, plastic, or any other material, since the electromagnetic wave is evanescent in the outer regions. With this alignment method, the plate distance is not variable. Another method of aligning the plates was proposed in [10] and realized in [11], as shown in Figure 2(b). By means of a vice, the plate distance is adjusted with a micrometer screw. This method works reasonably well only for small-sized groove-guide structures. For larger groove guides, this construction becomes too bulky. In the present work, the plates were aligned by metallic posts as shown in Figure 2(c). Many posts of different heights are available to realize an adjustable plate distance. However, only discrete values of the plate distance are realizable.

The groove guide has the advantage of being low-loss as well as having an open structure. Commonly used transmission lines such as coaxial cable, microstrip line, and hollow waveguide are constructed from mechanically interconnected pieces. The groove guide, however, consists of two separate parallel plates whose separation distance can be adjusted, thereby affecting the frequency of operation of the guide itself. Furthermore, materials can be easily inserted to the groove region. For the case where a dielectric sheet is inserted, the sheet will affect the frequency of operation. Both features, the open structure and the tunable nature of the groove guide, can be exploited to create measurement systems, as shown in the following.

Figure 3 depicts three possible applications of the groove guide for industry. The first two applications are distance meters. In Figure 3(a), a movable groove guide hovers at a distance *h* above a metallic surface. The distance can be measured while moving the groove guide above the surface. In Figure 3(b), the groove guide is mounted close to a metallic drum; for instance, a turbine. One plate of the groove guide is connected to the measurement system, and the metallic drum serves as the other plate of the groove guide. If there is any imbalance of the drum, the distance *h* changes, which is detected and evaluated by the distance measurement system. The second application, shown in Figure 3(c), is a dielectric meter. In the process of producing dielectric sheets, they are conveyed through the groove-guide structure. If the thickness *t* of the sheet is known, the permittivity ε_r can be determined, and vice versa. In both applications, the accuracy of the groove guide methods is not generally as high as with other methods, which will be discussed later. However, other benefits may outweigh the loss in accuracy in many applications. Both

As its name implies, the ring-shaped groove-guide resonator is a closed 360° groove-guide bend.

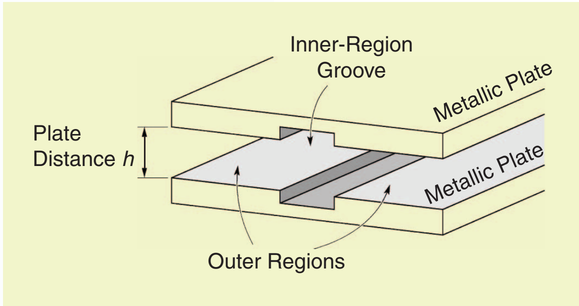


Figure 1. *Groove guide of rectangular cross section proposed by Tischer [1].*

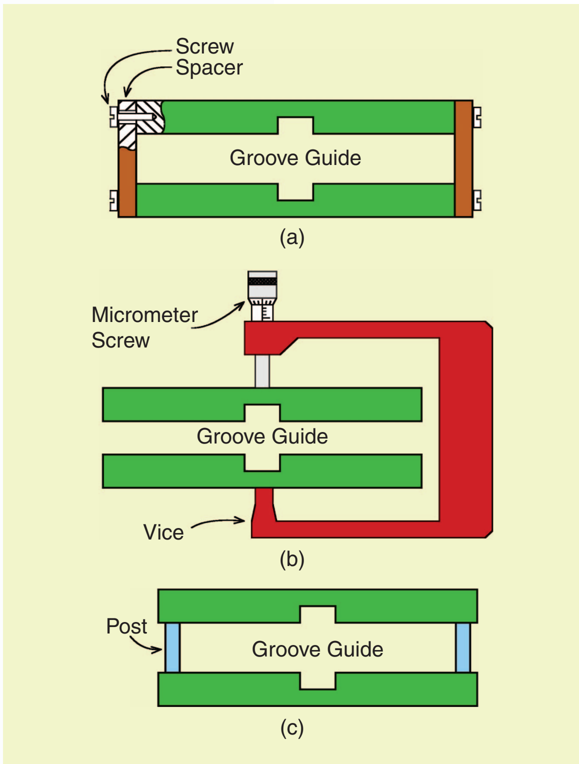
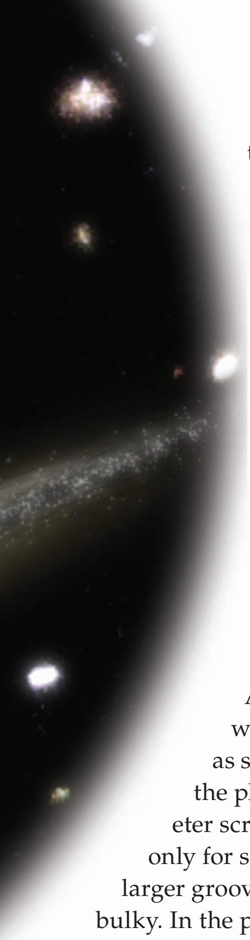


Figure 2. *Plate distance maintained with (a) spacers, (b) a vice and micrometer screw, and (c) posts.*



In practice, it is difficult to align the two plates in such a way that the two grooves are exactly facing each other.

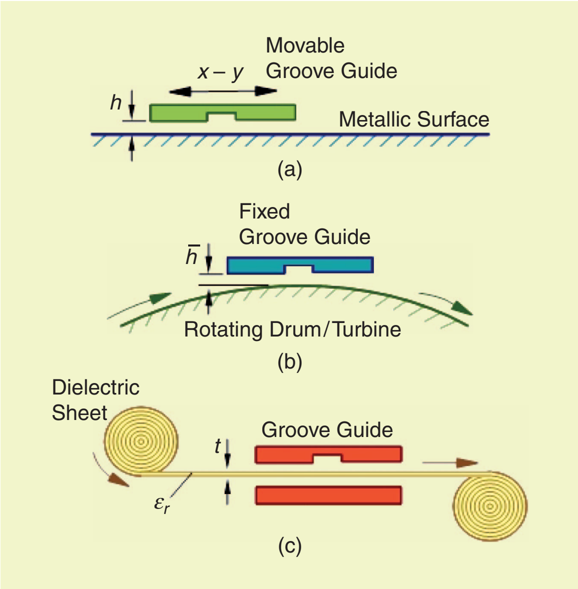


Figure 3. *Possible industrial applications for the groove guide oscillator: (a) and (b) distance measurement and (c) permittivity measurement.*

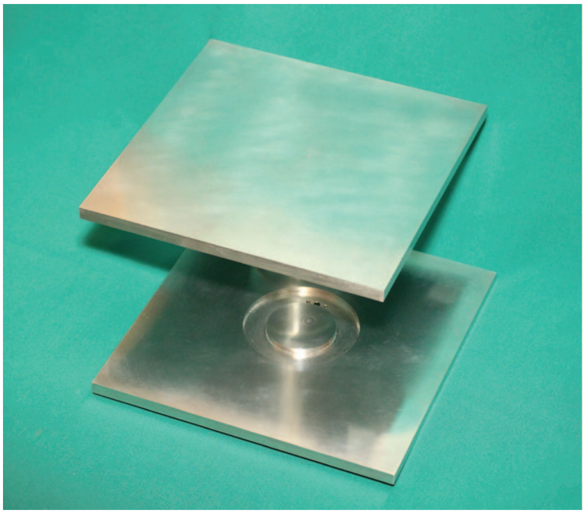


Figure 4. *Photograph of a ring-shaped groove-guide resonator operating in the X-band (8–12 GHz).*

systems, distance and dielectric meter, will be discussed in more detail in later sections.

The Groove Guide Resonator

As for any other waveguide, standing waves in a groove guide along the direction of propagation are commonly obtained by either total reflection at both ends or by forming a closed loop [12]. The first type of groove guide resonator was realized by Choi [13]. Metallic plates at both ends serve as short circuits. To tune the resonant frequency, Choi implemented at one end a variable positioned short-circuit. The plate distance was kept constant. The second type of groove guide resonator was manufactured and investigated by Vertiy et al. [14]. The resonator was ring shaped, and its resonant frequencies were dependent on the mean diameter D and plate distance h, whereas the plate distance was variable. As its name implies, the ring-shaped groove-guide resonator is a closed 360° groove-guide bend.

Propagation properties, especially radiation losses, of groove-guide bends have been studied by Thiébaut and Roussy [10] and Meißner [15]. Manufacturing both the bend radius of the ring-shaped resonator and the dimension of the outer regions large enough keeps such radiation losses at a negligible minimum. In [11], Bechteler and Sevgi summarized current knowledge about the ring-shaped groove guide resonator and included numerical investigations using the FDTD method. In practice, it is difficult to align the two plates in such a way that the two grooves are exactly facing each other. Therefore, it has been proposed to have only one plate with a groove. The other plate is planar. This new structure has been termed the "semisymmetrical groove guide" [14]. Figure 4 shows a photograph of the semisymmetrical groove guide resonator used in the examples that follow. Its bottom plate is grooved, and its top plate is planar. The dimensions of the ring resonator used for the measurement system are listed in Table 1. It has been designed and manufactured to operate in the X-band, between 8 GHz and 12 GHz.

TABLE 1. Dimensions of the groove-guide resonator used.

Parameter	Value
Mean Ring diameter D	60 mm
Groove depth d	5 mm
Groove width w	15 mm
Plate distance h	13–15 mm, variable
Dimensions of the plates	200 × 200 mm^2

The Groove-Guide Oscillator

To induce oscillations of the groove guide resonator, a negative resistance has to be implemented. Harris and Mak [16] and Shi et al. [17] generated oscillation in a standard waveguide cavity by means of an IMPact Avalance and Transit Time (IMPATT) diode and a Gunn device, respectively. In both works, the oscillation was coupled via an adapter to a groove-guide structure. This adapter, also termed a "transformer" [16] or a "taper" [17], was introduced by

Griemsmann [2] as a mode launcher for groove guides. However, it is desirable to induce oscillations directly inside the groove region. Hence, the negative resistance must be placed inside the groove. A Gunn element was selected to provide this negative resistance. The disadvantage of Gunn elements is their low output power of about 100 mW at 10 GHz. The advantage is that they are quite simple to bias. Two matters must be considered with the use of a Gunn element: biasing of the element and coupling of the induced microwave signal into the element. Various coupling structures were presented, for instance, in [14] and [18]–[20]. Vertiy et al. [14] employed slot coupling for the groove guide. This was investigated in more detail by Bechteler et al. in [19] and [20]. The disadvantages of slot coupling are that it is expensive to manufacture, and biasing of the Gunn element is not directly possible. Harris and Mak [18] used a tiny dipole inside the groove region to couple the microwave signal. Their intention was to detect a microwave signal with a beam lead diode implemented in the dipole. However, because an antenna is a reciprocal device, it can be used to induce oscillation. For this case, the beam-lead diode could be replaced by a Gunn element. A simpler coupling is the loop coupling [20], which has, to date, proved to be the most convenient coupling. It achieves two objectives at the same time. First, it supplies the Gunn element with the bias voltage. Second, it couples the microwave power from the groove region to a coaxial line. Figure 5 shows a photograph of the coupling loop inside the groove region. The loop was optimized to operate in band from 8 to 12 GHz, that is, the loop diameter is about 10 mm and the wire thickness is 0.6 mm. The Gunn element used in [20] requires a bias voltage of about 5 V and draws a bias current of about 1 A. The anode of the Gunn element is connected to the loop wire. The cathode is fitted into a hole inside the groove. Hence, the grooved metallic plate serves as an electrical ground and as a heat sink.

In Figure 6, measurements of the response of a groove-guide resonator are compared with measurements of response of a groove-guide oscillator. The distance h between the metallic plates was changed from 13 mm to 15 mm. The resonance spectra of the groove-guide resonator and oscillator were measured with a network and a spectrum analyzer, respectively. Note that, when the plate distance is increased, the resonant frequency decreases. All measurements agree to within 80 MHz. Differences between resonator measurements and oscillator measurements are mainly due to two effects: 1) the reactive component of the Gunn element's impedance, which is explained in more detail later in this article and 2) the setting accuracy of plate distance h. Figure 6 shows only the resonant frequency of the fundamental mode. Higher modes are not shown. If the

Because an antenna is a reciprocal device, it can be used to induce oscillation.

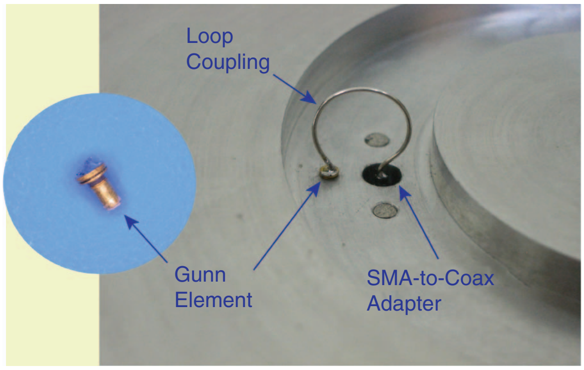


Figure 5. *Close-up photograph of the coupling loop that biases a Gunn element inside the groove of the groove-guide oscillator.*

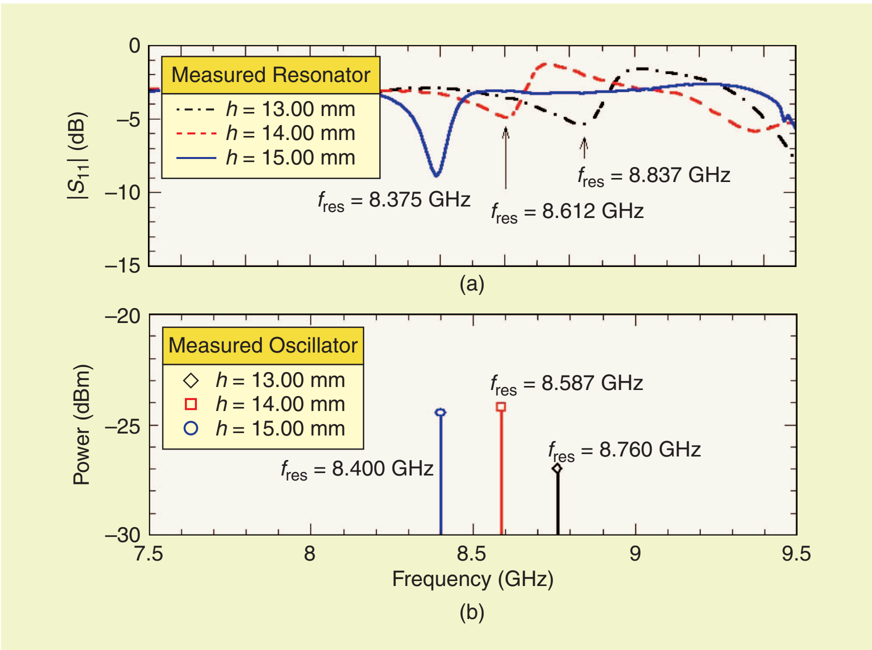


Figure 6. *Measurements of a groove-guide resonator (measurements made with a network analyzer) and the groove-guide oscillator (measurements made with a spectrum analyzer).*

When the plate distance is increased, the resonant frequency decreases.

aforementioned plate distance range of 13–15 mm is exceeded, the higher modes fall into the frequency range of interest. In this case, uniquely identifying the resonant frequency with the plate distance is not possible anymore.

In Figure 6, the reflection measurements of the resonator were performed while the Gunn element was in place but not biased. Since the coupling loop is designed to obtain maximum coupled power—necessary because of the low power delivered by the Gunn element—the loaded quality factor is calculated from the measured curves to be $Q_L = 100$. The load in the case of the measured resonator was the network analyzer and in the case of the measured oscillator, the spectrum analyzer, each with an impedance of approximately $50\,\Omega$. Furthermore, the unbiased Gunn element causes additional losses, which deteriorate the quality factor, though to a smaller extent. Therefore, the difference shown in Figure 6(a) is small between the measurements without and Figure 6(b) with biasing applied to the Gunn diode. Loaded quality factors between 300 and 400 have been reported in [11] where no Gunn element was implemented and where the groove-guide resonator was weakly coupled via tapered waveguide slots. For the case discussed here, the unloaded quality factor could not be determined because the coupling structure could not be calibrated.

Heterodyne System—A Standard System

Heterodyne systems are standard systems used in RF receivers to detect signals carrying information with the aid of a local oscillator [21]. Thus, the information, in this case the change in the resonant frequency of the groove-guide oscillator, is obtained for further processing.

In order to use the groove-guide oscillator for distance or permittivity measurements, a standard heterodyne system may be realized. A block diagram and photograph of the heterodyne system are shown in Figures 7 and 8, respectively. The antenna in a standard receiver is replaced by the manufactured groove-guide oscillator, which provides the microwave signal to be evaluated. Furthermore, a bias-T circuit, a mixer connected to a local oscillator, and a low-pass filter are part of the heterodyne system. Additionally, a frequency counter and a laptop computer are connected to the measurement system. The groove-guide oscillator works as an active sensor in the X-band. The heterodyne system receives the oscillator's resonant frequency, which is converted via the mixer to a frequency less than 2.5 GHz. The value of the resonant frequency is measured by the counter and read out by the computer for further data processing. The computer converts the frequency or the permittivity to distance by use of calibration data. Furthermore, it displays the determined distance or permittivity on the screen.

The accuracy [22] with which the resonant frequency is determined depends on the bias stability of the Gunn element, the phase noise of the local oscillator, and the error of the frequency counter. All of these errors are random errors [22]. The error of the frequency counter was given to be ± 1 kHz in the manufacturer's specifications. The phase noise of a representative local oscillator was measured to a single-sideband noise level of -83 dBc/Hz at an offset frequency of $\delta f = 100$ kHz. The frequency error of a representative groove-guide oscillator was determined to be ± 5 MHz and is due to

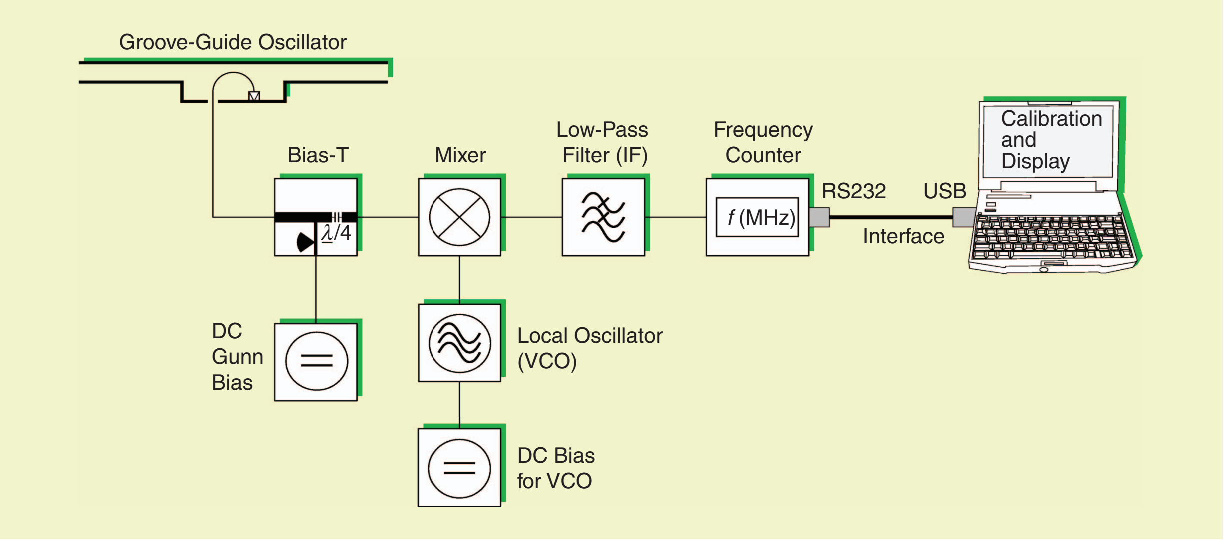


Figure 7. *Block diagram of the heterodyne measurement system.*

the slightly imperfect Gunn biasing voltage. This biasing voltage fluctuates because of noise and a ripple of a few millivolts of the dc power supply.

Application 1: Distance Meter

The first application discussed here is a distance meter. Distance meters operating with microwave signals can be classified as radar systems and as resonator systems. The first class of distance meters, that is, radar systems, were originally designed to locate, at a far distance, an object that reflects radio waves. For some industrial applications, such systems have been optimized for short ranges. In [23] for example, ultrawideband (UWB) radars, which operate in the range of a few meters with an error of a few centimeters down to several millimeters were described. A much more accurate radar system was presented in [24]. The system of [24] shows a very small error of less than 10 μm within a measurement range of 0–100 mm. Uncertainties are explained and compared with those of other systems later in this section. This system was designed to measure the eccentricity of rotating elements as illustrated in Figure 3(b).

The second class of distance meters employs resonators whose resonant frequencies are changed by a change in the resonator's dimensions. Depending on the operating frequency, the resolution of such distance meters can be as low as 1 μm. For instance, with the patented system in [25], the resonant frequency of a cylindrical cavity resonator is affected by an approaching conductive surface. The operating frequency is about 24 GHz, the measurement range is between 0.2 mm and 4 mm, and the resolution is better than 1 μm.

The groove guide-oscillator as a distance meter has been reported in [26]. As mentioned before, the groove-guide oscillator consists of two separate metallic plates that are arranged in parallel. The distance between these parallel plates defines the resonant frequency of the oscillator. When the distance is increased, the resonant frequency decreases, and vice versa. Figure 9 depicts the distance versus frequency behavior for three situations: 1) numerical simulation, 2) measurement of the passive resonator, and 3) measurement of the oscillator. For the FDTD simulations the groove-guide structure was discretized in a Cartesian coordinate system with a cell size of $\Delta x = \Delta y = \Delta z = 0.25$ mm, which is one-hundredth of the wavelength of the microwave signal. Consequently, the FDTD algorithm for the groove guide with the maximum dimensions given in Table 1 requires a relatively large memory size of about 6 GB. The plate distance was changed from 13 mm to 15 mm in 0.25 mm steps. For the measurements, the plate spacing was changed in 1 mm steps. All data points were linearly interpolated as shown in Figure 9.

Distance meters operating with microwave signals can be classified as radar systems and as resonator systems.

In Figure 9, comparing blue curve (a) with red curve (b) reveals a frequency shift, while the slope is approximately the same for the two curves. This frequency shift is due to manufacturing errors in the groove, which were determined to be on the order of 0.1 mm. The most sensitive parameter is the groove depth d. The mechanical error of 0.1 mm for d results in a shift of the resonant frequency of about 100 MHz. This error is systematic for a particular unit and can be eliminated by a calibration

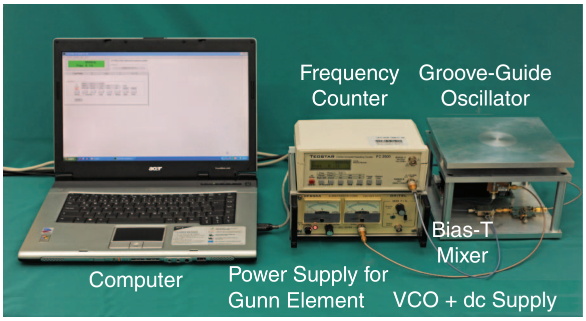


Figure 8. *Photograph of a heterodyne measurement system.*

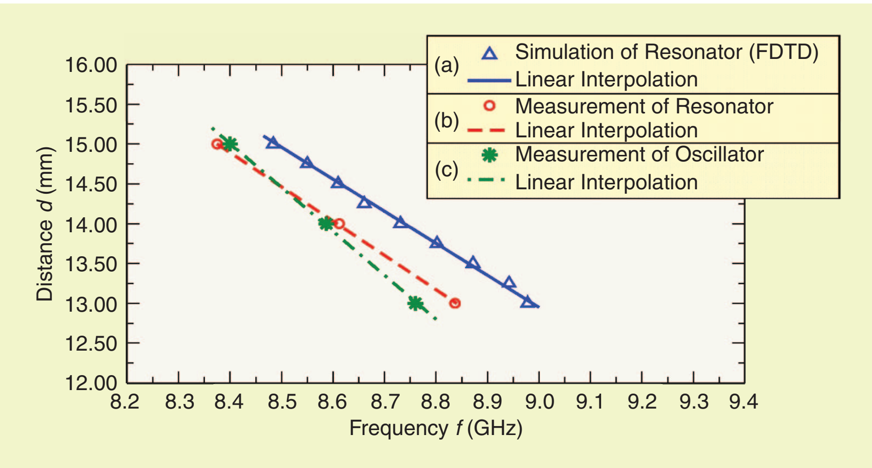


Figure 9. *Distance versus resonant frequency: (a) FDTD simulation of resonator—no Gunn element, (b) measurement of resonator—Gunn element placed but not biased, and (c) measurement of oscillator—Gunn element biased.*

The difference between the theoretical resonant frequency and the measured resonant frequency provides the calibration coefficients.

TABLE 2. Technical features of distance meters.

System	Venot and Wiesbeck [24]	ASTYX [25] (commercial)	Bechteler [26]
Method	Continuous wave (CW) radar	Cavity resonator	Groove-guide oscillator
Operating frequency	76.5 GHz	20–30 GHz	8–12 GHz
Distance range	0–100 mm	0.2–4 mm	13–15 mm
Measurement error	$< \pm 10\ \mu m$	$< \pm 1\ \mu m$	$\pm 30\ \mu m$

procedure. Manufacturing another groove-guide structure requires a new calibration for the new unit. Running the FDTD simulations with a cell size equal to or less than the error of 0.1 mm requires a large amount of computer memory, which is not available to the authors for the time being. Thus, to calibrate the groove-guide structure, posts of different, specified heights were produced. For each post, the resonant frequency of the oscillator was measured. The difference between the theoretical resonant frequency and the measured resonant frequency provides the calibration coefficients. However, as mentioned above, the accuracy in setting a plate to distance h depends on the manufacturing error of the posts, which is a random error. The error for the length of the posts was given by the manufacturer to be $\pm 10\ \mu m$, which results in an additional error in the frequency of the oscillator of ± 10 MHz.

Again, in Figure 9, when comparing red curve (b) with green curve (c), the latter curve is tilted. This is attributed to the reactive part of the Gunn element's impedance. Since no data sheet for the Gunn element was available to provide the value of the impedance, the difference between curve (b) and curve (c) could not be quantitatively assessed. However, the tilting between curves (b) and (c) can be qualitatively explained by using the transverse resonance method of Oliner et al. [3]. This method models the cross section of the groove-guide transverse to the propagation direction and leads to an implicit function in the resonant frequency of the groove-guide resonator. This model has to be extended with the impedance of the Gunn element. For instance, assuming a capacitance and solving the extended implicit function with respect to the resonant frequency for different plate distances h reveals that the resonant frequency shift is greater for a smaller plate distance. Hence, curve (c) in Figure 9 is tilted. This error is also systematic and is eliminated by the calibration method mentioned above. By use of linear interpolation of the oscillator measurement, an equation for curve (c) is obtained, which is stored on the computer for calibration. Thus, the measured resonant frequency is converted into a distance value according to (1).

$$f_{res} = -0.181 \cdot h + 11.12\ (\text{GHz}), \quad (1)$$

where f_{res} and h are given in GHz and mm, respectively. For the example shown here, moving the plate

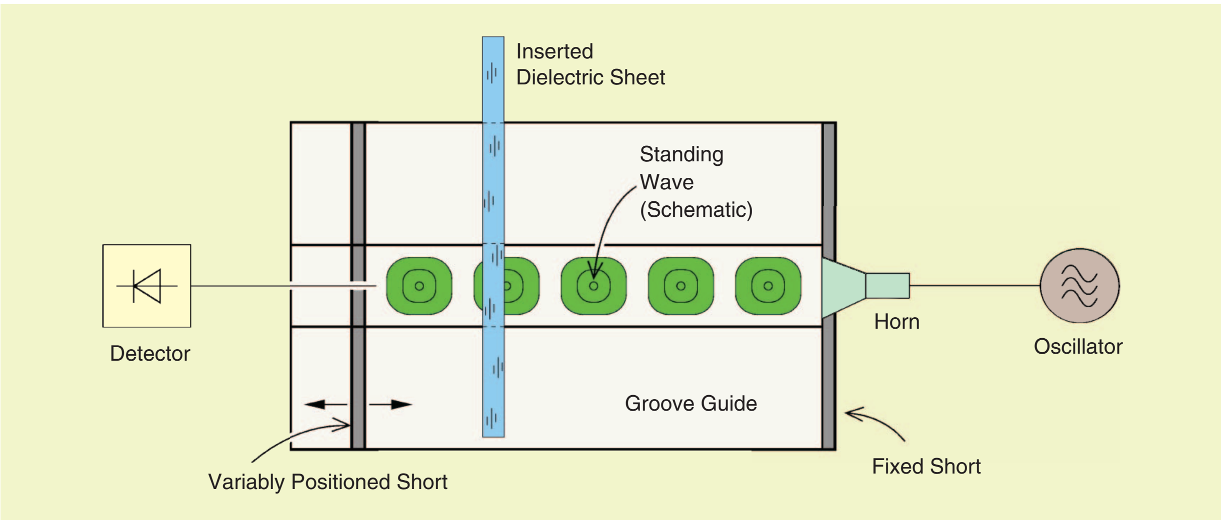


Figure 10. *Permittivity measurement after Choi [13]—top plate removed.*

a distance of 0.1 mm results in a resonant frequency change of 18.1 MHz. As mentioned previously, the accuracy with which the distance can be measured is limited by the frequency stability of the groove-guide oscillator. The frequency stability depends on the Gunn element's biasing stability, and this frequency error has been determined to be $\pm$ 5 MHz. This is a random error, which results, according to (1), in an error of $\pm$ 28 μm. Since this error is not correlated to the accuracy of setting the plate distance for the calibration procedure, both errors can be summed up by adding their squares [27]. Therefore, the distance measurement error is $\pm$30 μm. It is interesting that, although the wavelength of the resonant frequency is about 30 mm, the measurement accuracy of the system is in the submillimeter range. The most important features of the distance measurement systems of [24]–[26] are summarized in Table 2.

Application 2: Permittivity Measurement

The second application is a permittivity measurement system. Since the two plates of the groove guide oscillator are separated from each other, materials can easily be inserted between the two plates. In a technical memorandum, Choi [13] investigated a permittivity measurement system operating at 100 GHz. As shown in Figure 10, a groove guide shorted at both ends was driven with a microwave signal of fixed frequency. With a variably positioned short circuit at one end, resonance was established. When a dielectric material was inserted, resonance had to be reestablished by changing the position of the variable short circuit. Due to this change of position, the permittivity was calculated. Using this technique, both permittivity and loss tangent of a material can be determined with an accuracy of $\pm$6 % and $\pm$50 %, respectively. The measurement procedure, however, is tedious and therefore not suitable for continuous measurements.

In [28], Li et al. presented a permittivity measurement system working in the X-band that permits continuous measurements. As shown in Figure 11,

The electromagnetic field is stronger inside the groove and weaker close to the plane plate.

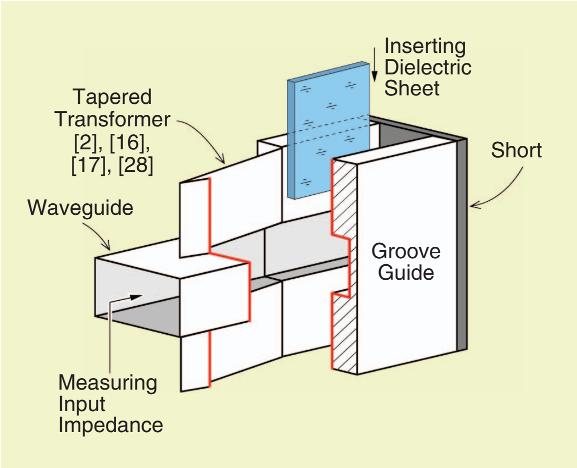


Figure 11. *Permittivity measurement after Li et al. [28]—broken-out section view.*

a rectangular waveguide was flanged via a tapered transformer to one side of a groove guide. The other side of the groove guide was electrically shorted. Li et al. measured the input impedance of the shorted groove guide. This input impedance changes according to the dielectric material that is inserted into the groove guide. No statement was given about the accuracy of the measurements. Tests were performed for granular materials. Obviously, this system could also be used for dielectric sheets.

Another method for finding permittivity is to use the groove-guide oscillator described in this work. For calibration purposes, 1.5 mm thick dielectric sheets having well-known permittivities are inserted into the guide one at a time, as shown in Figure 12. The resonant frequency is then measured. In Figure 13, both the simulation and measurement points are plotted, along with their corresponding linearly interpolated curves. Analogous to the

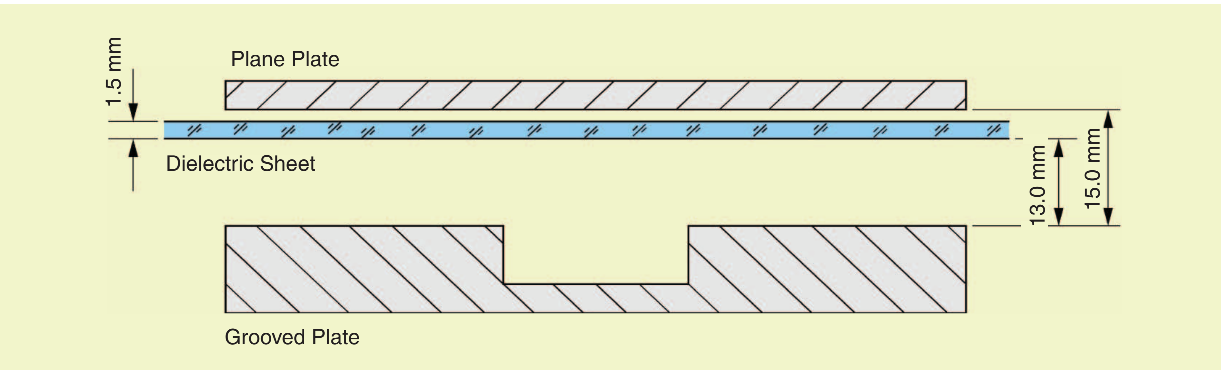


Figure 12. *Insertion of a dielectric sheet into the groove-guide oscillator.*

The oscillation frequency can be easily adjusted by changing the distance between the two plates or by inserting material between the two plates.

distance meter, the difference between blue curve (a) and green curve (b) is due to systematic errors of the mechanical fabrication process of the groove and the Gunn element's impedance. According to FDTD simulations, the relationship between f_{res} and ε_r becomes strongly nonlinear for permittivities $\varepsilon_r < 1.5$. For cases where $\varepsilon_r > 5$, higher modes propagate within the frequency range of interest. This makes resonant frequency identification impossible, regardless of whether or not the permittivities are known. The permittivity is related to the resonant frequency in (2).

$$f_{res} = -0.087 \cdot \varepsilon_r + 8.441 \text{ (GHz)} \quad \text{for} \quad 1.5 < \varepsilon_r < 5. \quad (2)$$

As shown in Figure 13, changing the permittivity by 0.1 results in a resonant frequency change of approximately 8.7 MHz. The accuracy of the permittivity measurement is limited by two issues. First, as with the distance meter, the accuracy of the measured distance is limited by the frequency stability of the groove-guide oscillator. Second, a change of the position of the dielectric sheet inside the groove guide structure causes an additional random error. As shown in Figure 12, the dielectric sheet is placed 13 mm above the grooved plate. When the dielectric sheet is moved towards the grooved plate, the resonant frequency decreases, and vice versa. The reason for this effect is the inhomogenous field distribution between the two plates. The electromagnetic field is stronger inside the groove and weaker close to the plane plate. For instance, a change of the sheet's position from 13 mm of ±0.5 mm results in a change of the resonant frequency of ±10 MHz. Since the slight fluctuation of the bias on the Gunn element and the sheet position are not correlated, their random errors can be summed up by adding their squares [27]. Hence, when the position of the dielectric sheet can be kept

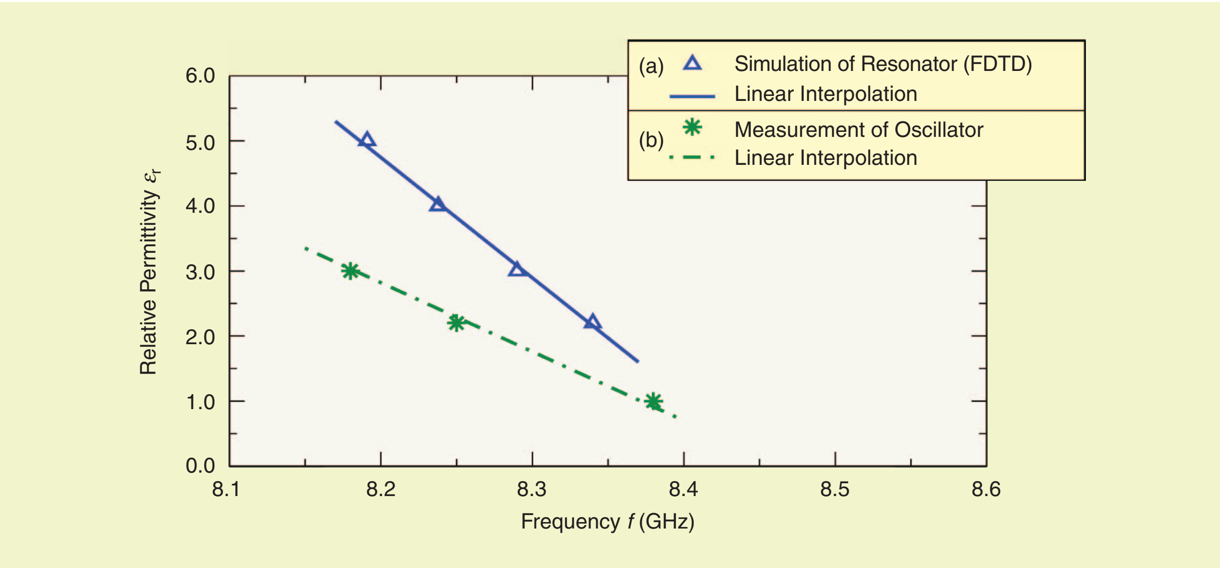


Figure 13. *Permittivity versus frequency where the dielectric sheet is placed as shown in Figure 10: (a) simulation of resonator—no Gunn element and (b) measurement of oscillator—Gunn element biased.*

TABLE 3. Technical features of permittivity meters.

System	This work	Choi [13]	Li et al. [28]	AET, Inc. [29] (commercial)
Method	Resonance	Resonance	Impedance	Resonance
Operating frequency	8–12 GHz	100 GHz	8–12 GHz	0.8–18 GHz
Sample size for dielectric material	Thickness 0.1–3 mm	Thickness 0.04 – 1.3 mm	Granular	Larger than 10×10×0.5 mm^3
Permittivity range	$1.5 \le \varepsilon_r \le 5$	$2 \le \varepsilon_r \le 3$	$1 \le \varepsilon_r \le 10$	$1 \le \varepsilon_r \le 15$
Loss tangent	Not possible	0.01–0.1	No data	0.001–0.1
Measurement error $\Delta\varepsilon_r$	±8%	±6%	No data	±1%

constant with a precision of ±0.5 mm, and taking into account the groove-guide oscillator frequency stability of ±5 MHz, the resulting measurement error of the permittivity $\Delta\varepsilon_r$ is ±0.13. This corresponds to a relative error of ±8%. The most important technical features of the permittivity measurement system are summarized in Table 3, where the examples presented here are compared to results from the aforementioned systems in [13] and [28], together with features of a patented commercial measurement system described in [29].

Conclusion

The groove-guide oscillator consists of two separate plates, between which a Gunn element is mounted to induce oscillation. The oscillation frequency can be easily adjusted in two ways, that is, by changing the distance between the two plates or by inserting material between the two plates. This expedient feature can be used to establish a versatile measurement system. Without a change of the groove guide's structure and employing a standard heterodyne system, distance and/or permittivity can be measured.

The often-quoted advantage that the groove-guide structure is larger and therefore easier to manufacture than other waveguides operating in the same frequency range turns into a disadvantage when designing sensors where small size is preferable. Nevertheless, this disadvantage may be acceptable given the groove guide's versatility in measurement systems.

While the accuracy of the groove guide methods is not generally as high as with other methods, other benefits may outweigh the loss in accuracy in many applications.

Acknowledgment

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