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Tsironis

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(54) **LOAD PULL SYSTEM USING TWO-PROBE WAVEGUIDE TUNER**

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(51) **Int. Cl.**

G01R 27/32	(2006.01)
G01R 31/28	(2006.01)
G01R 35/00	(2006.01)
H01P 5/04	(2006.01)

(52) **U.S. Cl.**
CPC ***G01R 27/32*** (2013.01); ***G01R 31/2822*** (2013.01); ***G01R 35/005*** (2013.01); ***H01P 5/04*** (2013.01)

(58) **Field of Classification Search**
CPC .. G01R 27/32; G01R 31/2822; G01R 35/005; H01P 5/04
See application file for complete search history.

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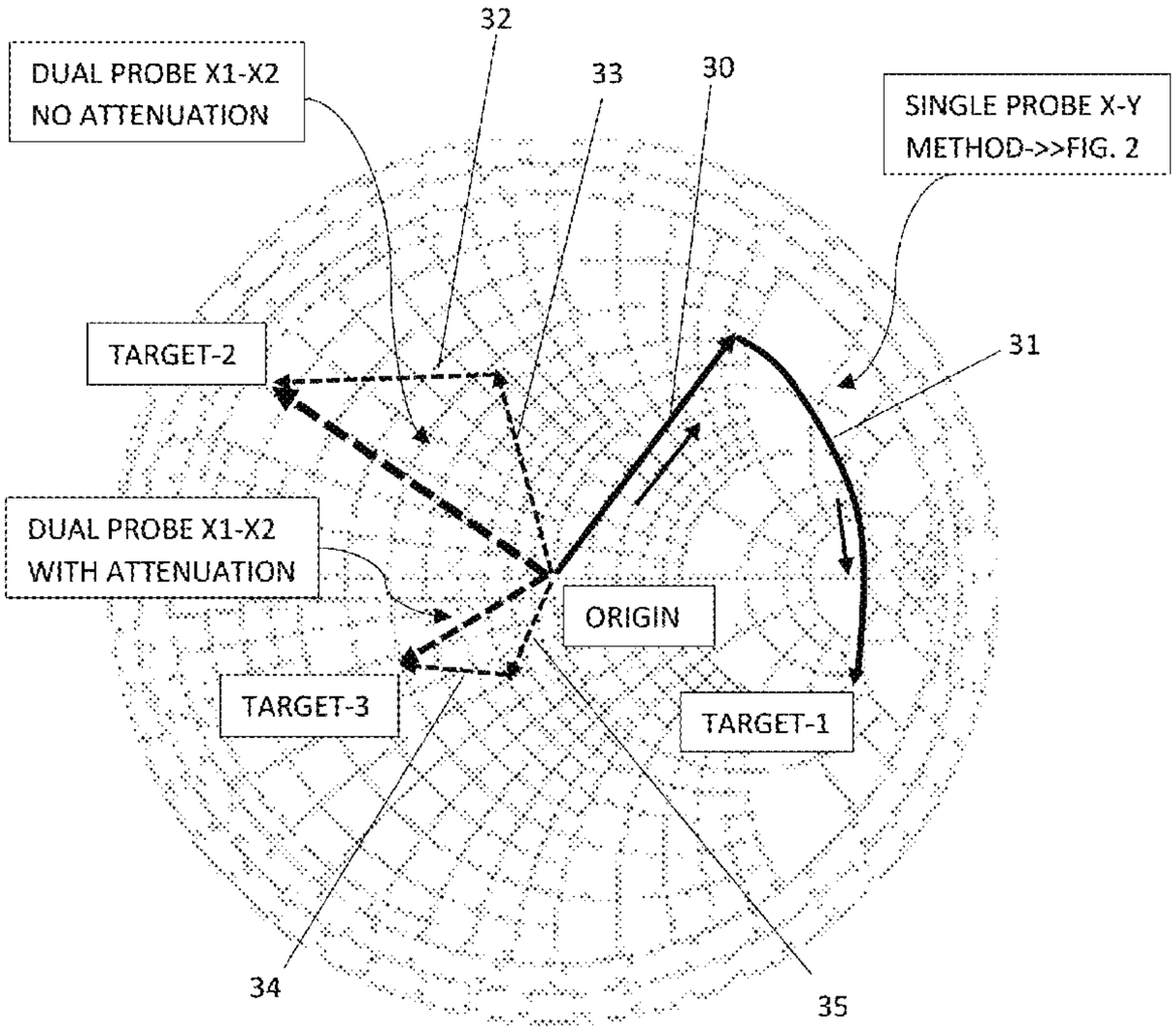
Assistant Examiner — Dilara Sultana

(57) **ABSTRACT**

A new load-pull tuner system using two-probe waveguide slide screw tuners of which the probes share the same waveguide section; they are inserted diametrically at fixed depth facing each other into slots on opposite broad walls of the waveguide. An adjustable broadband attenuator made using a resistive septum is inserted between the test port and the tuning probes. The tuner does not have cumbersome adjustable vertical axes controlling the penetration of the probes and its low profile is optimized for on-wafer operations. The carriages holding the probes are moved along the waveguide using electric stepper motors or linear actuators.

6 Claims, 15 Drawing Sheets



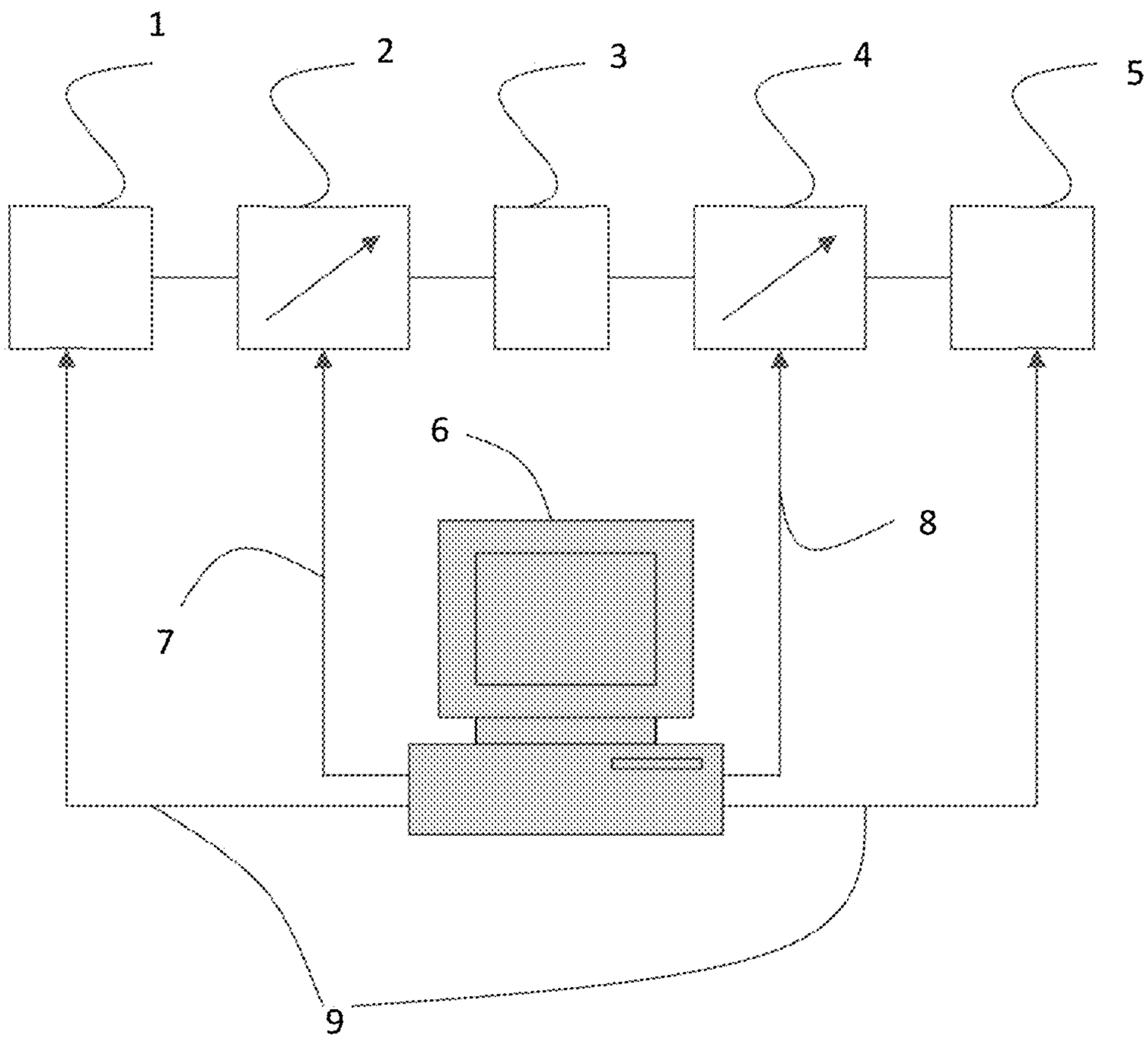


FIG. 1: Prior art

FIG. 2A: Prior art

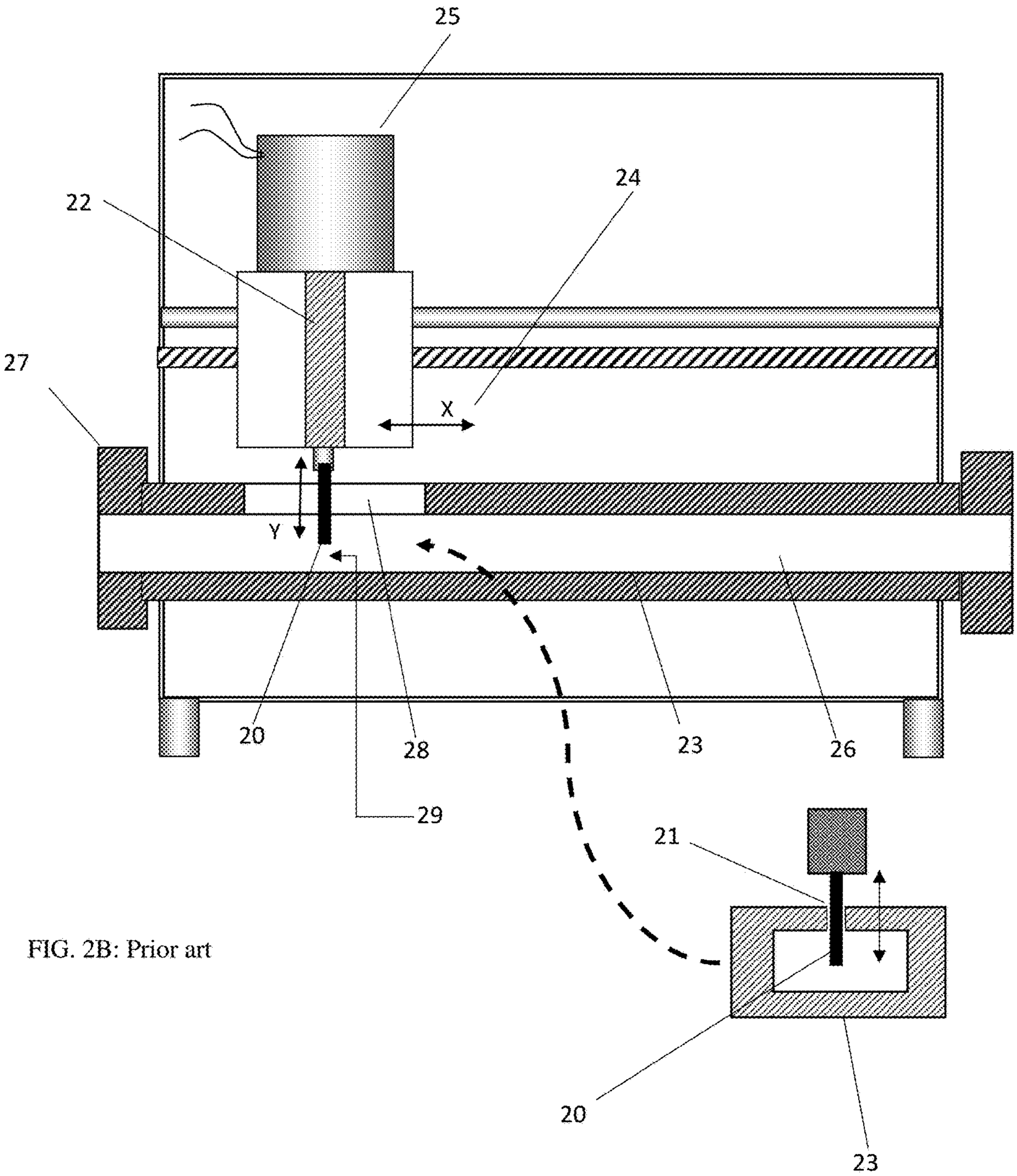


FIG. 2B: Prior art

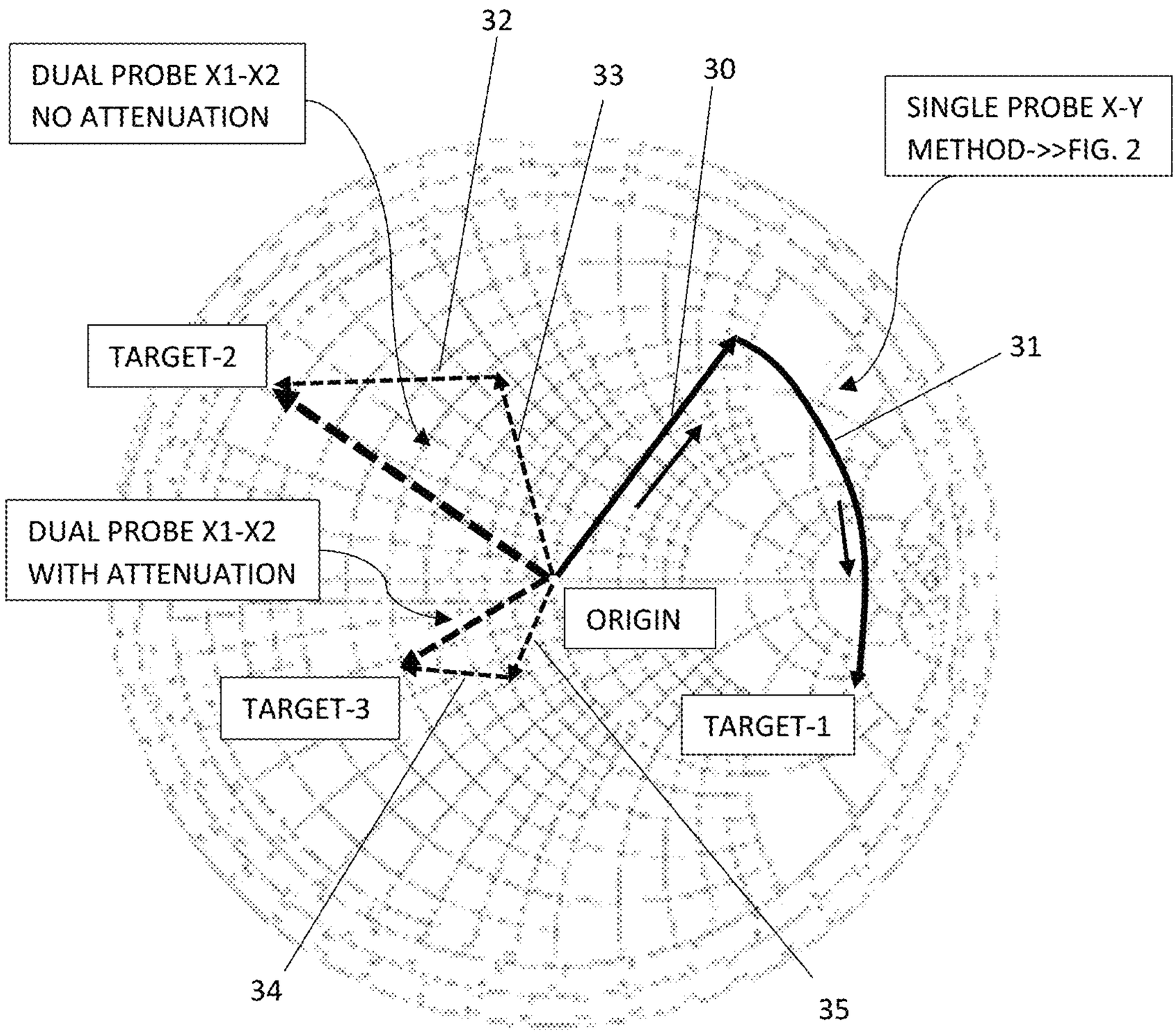

DUAL PROBE X1-X2
NO ATTENUATION
32
33
30
SINGLE PROBE X-Y
METHOD->>FIG. 2
TARGET-2
31
DUAL PROBE X1-X2
WITH ATTENUATION
ORIGIN
TARGET-3
TARGET-1
34
35

FIG. 3

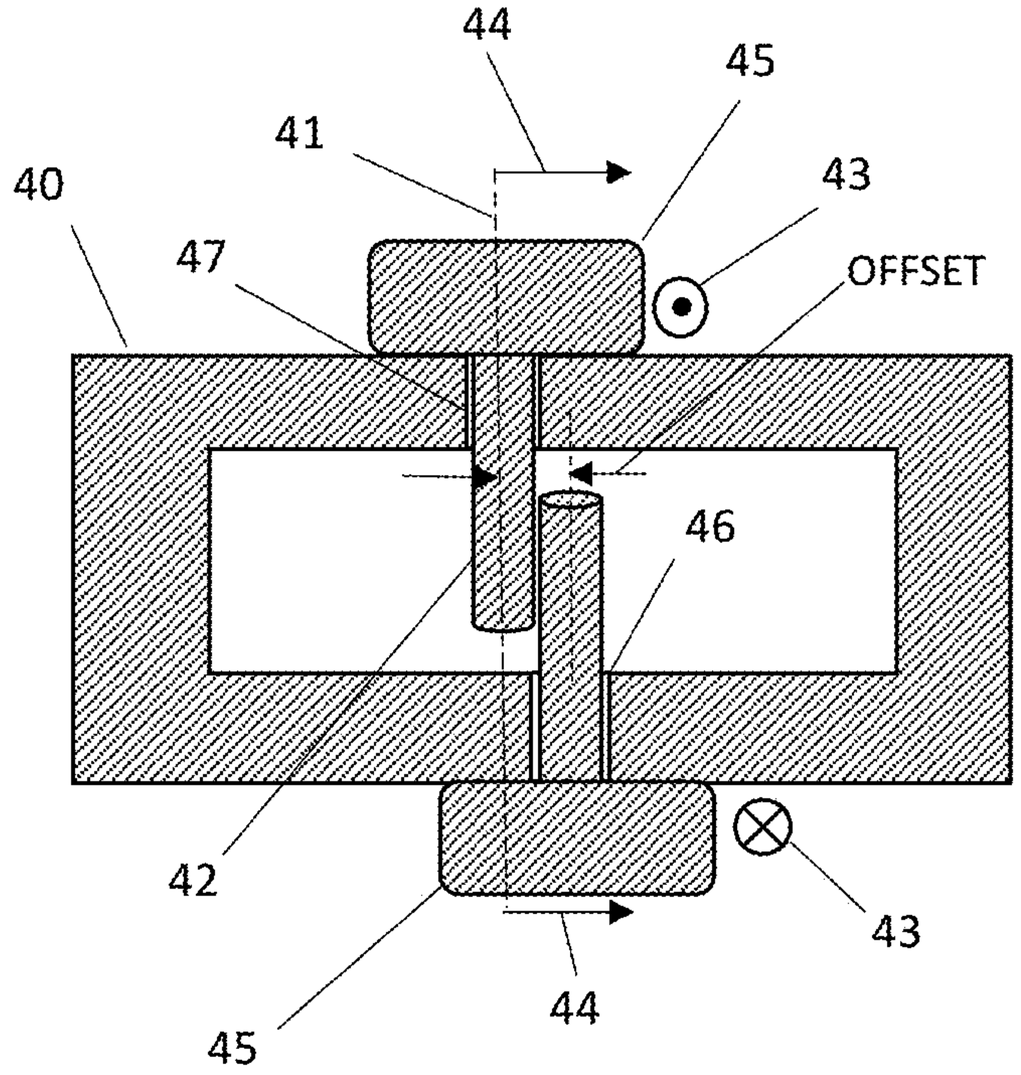


FIG. 4

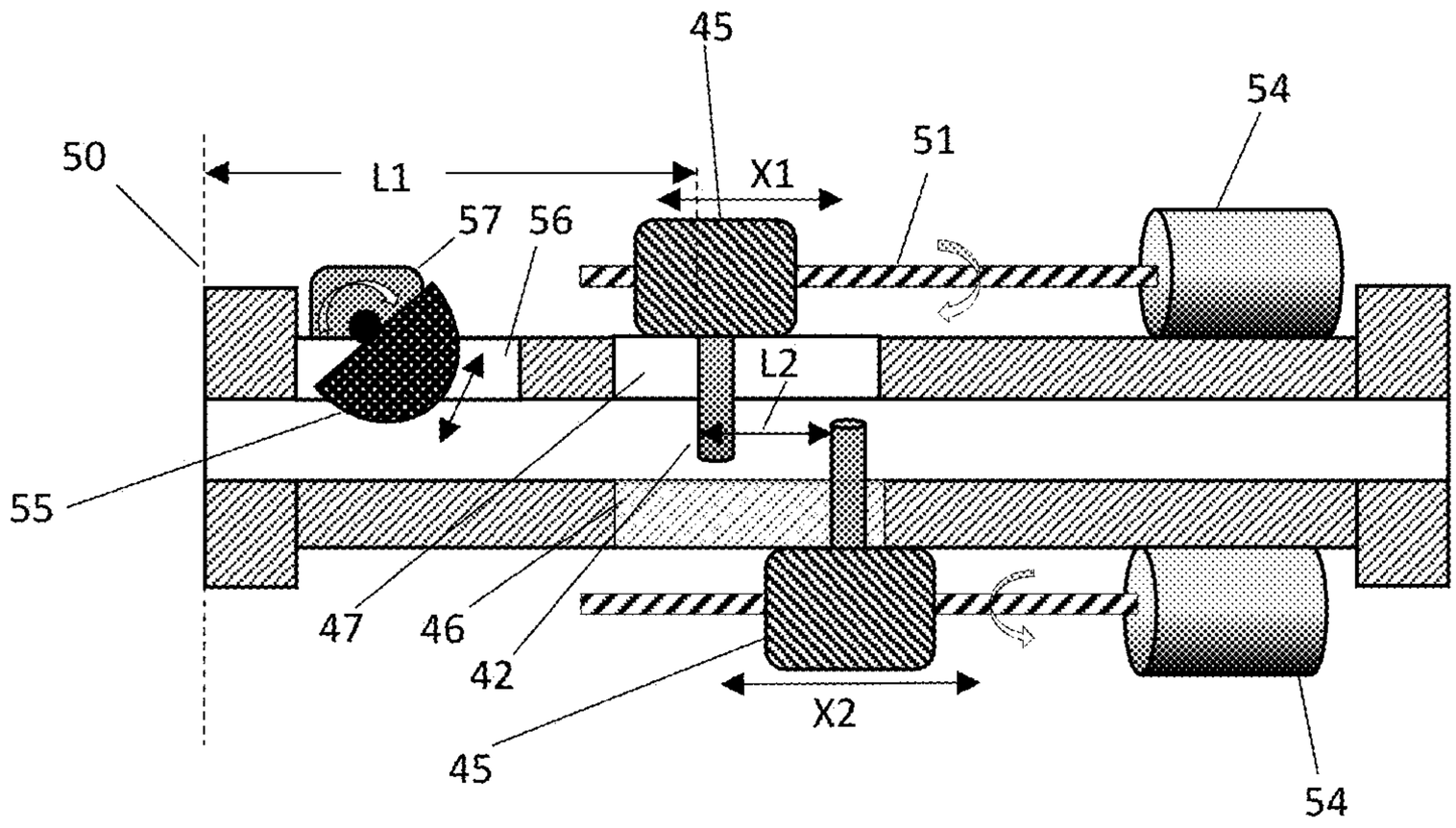


FIG. 5

FIG. 6A

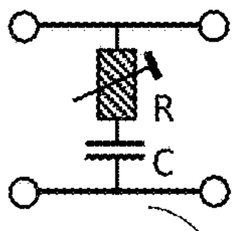


FIG. 6D

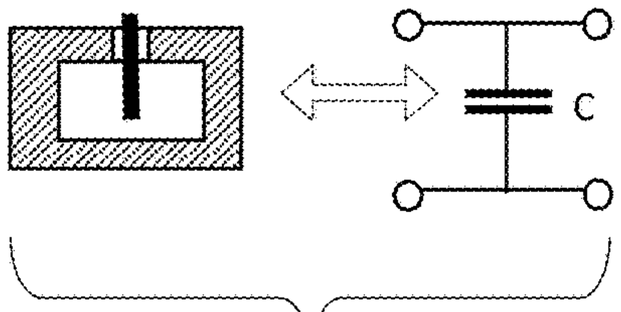


FIG. 6B

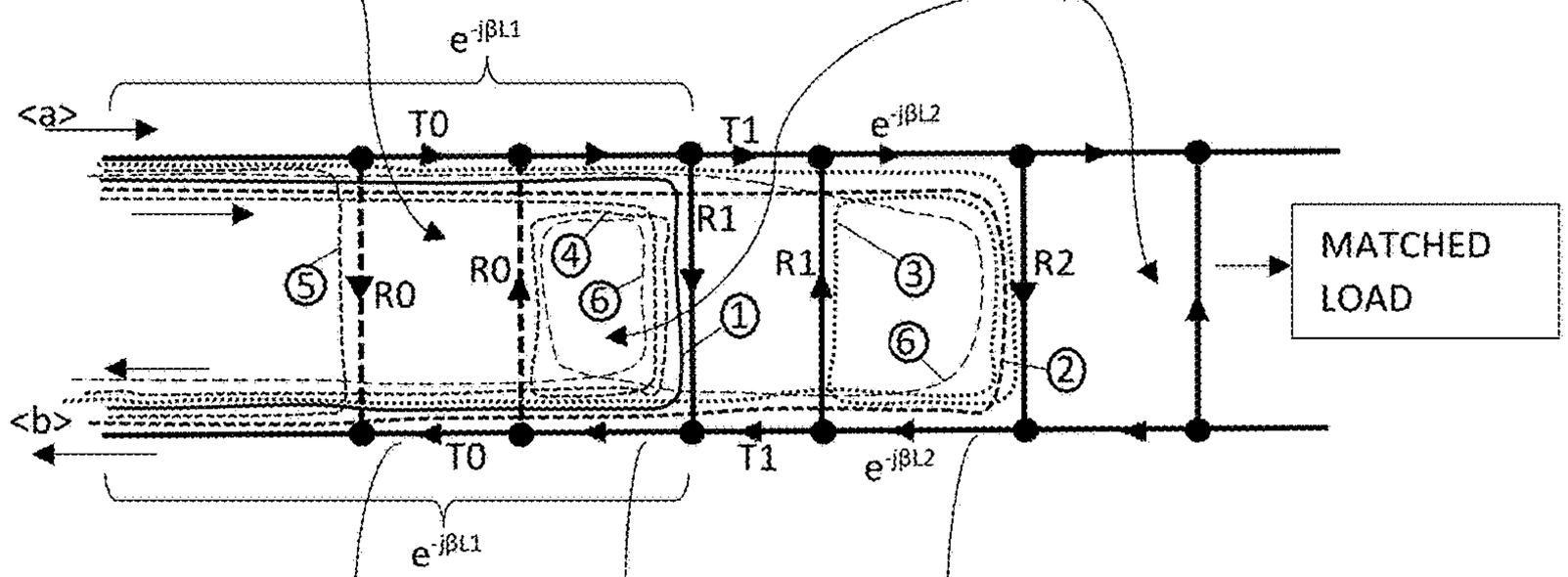
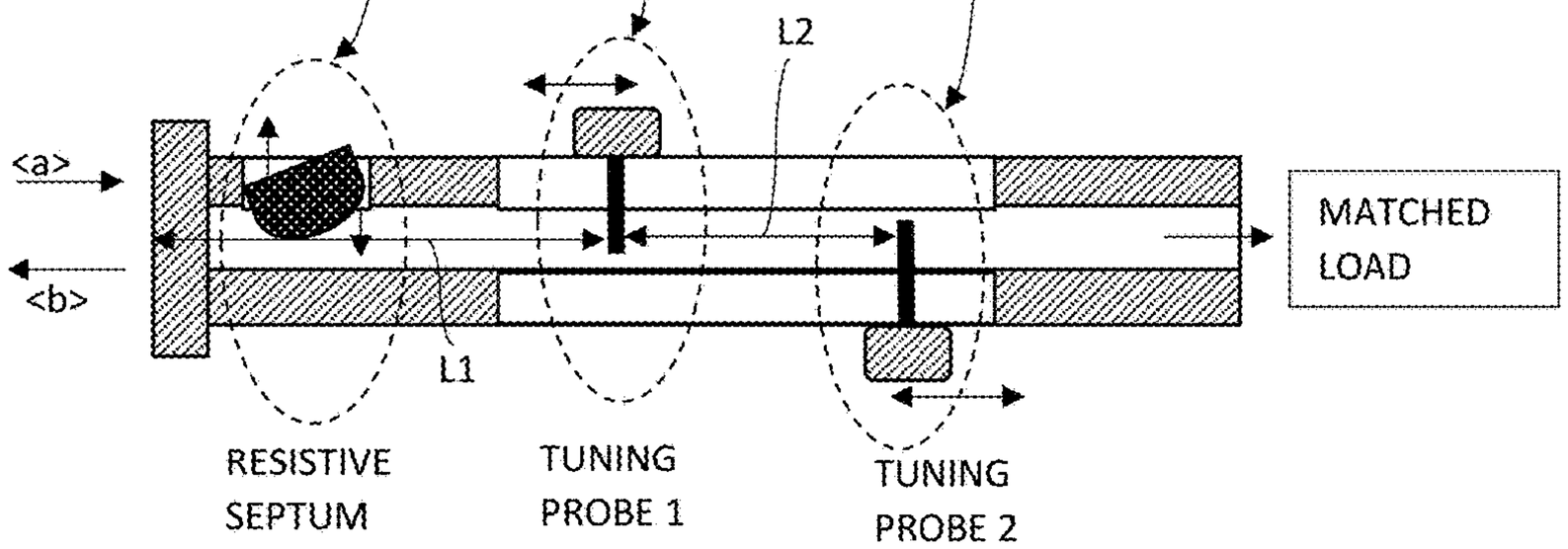


FIG. 6C



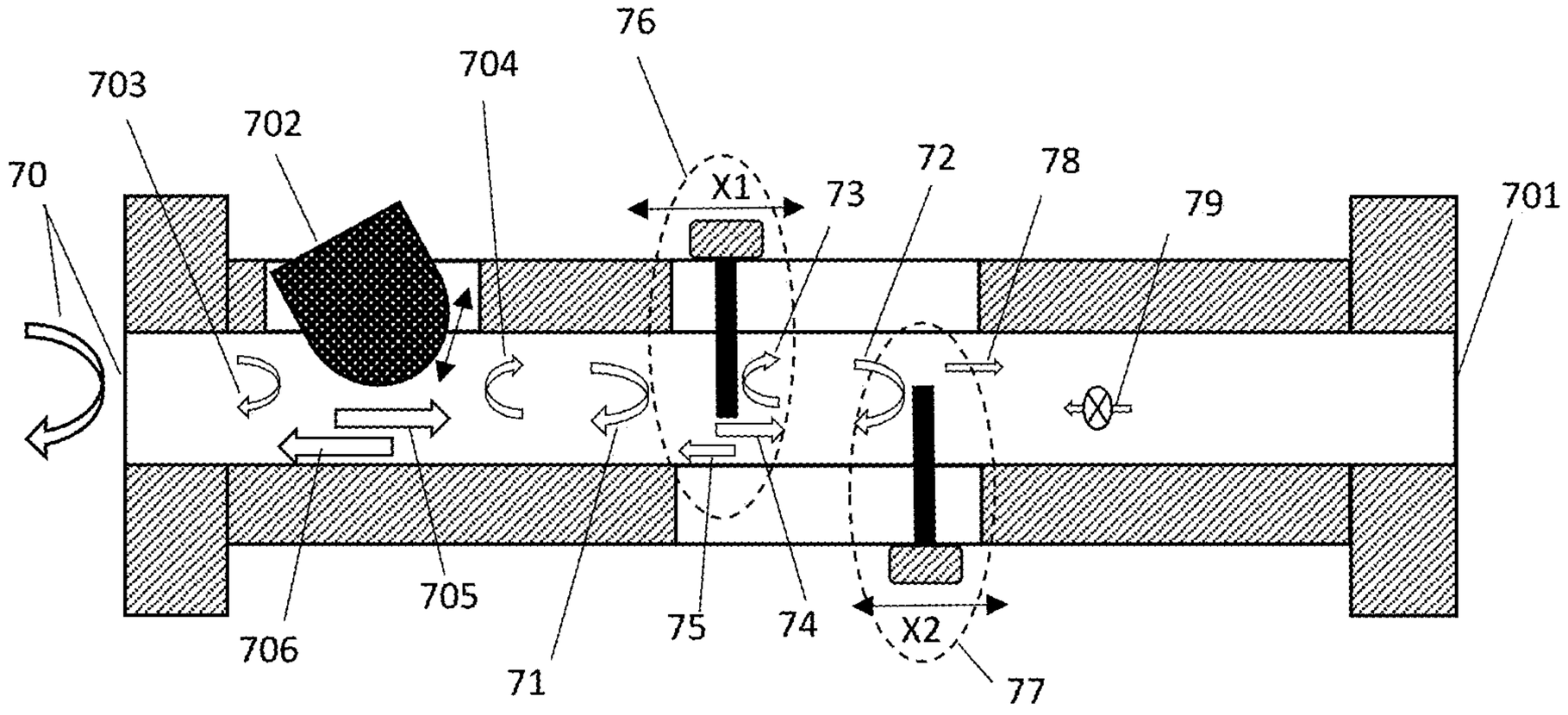


FIG. 7

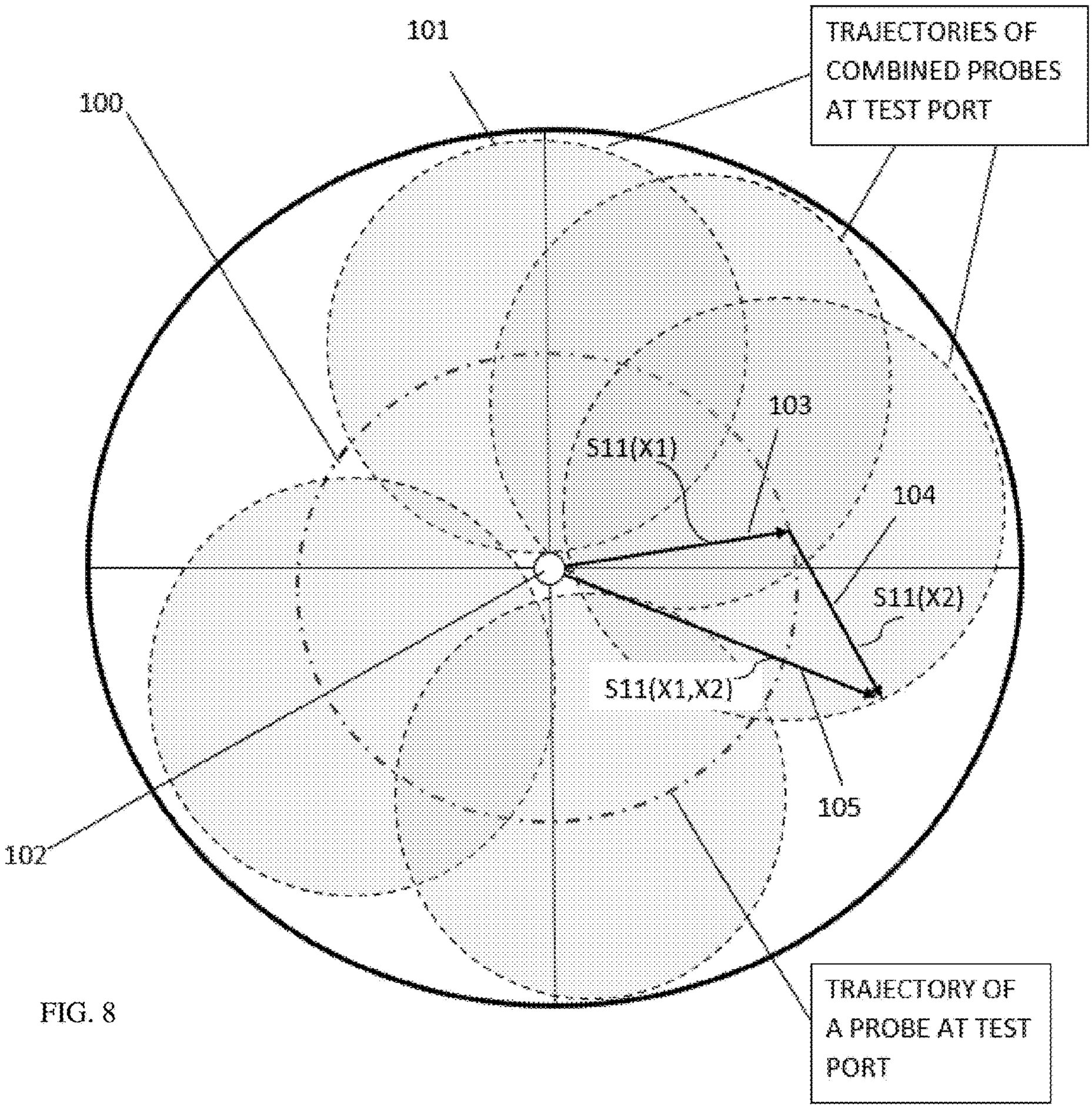

101
TRAJECTORIES OF COMBINED PROBES AT TEST PORT
100
103
S11(X1)
104
S11(X2)
S11(X1,X2)
105
102
TRAJECTORY OF A PROBE AT TEST PORT

FIG. 8

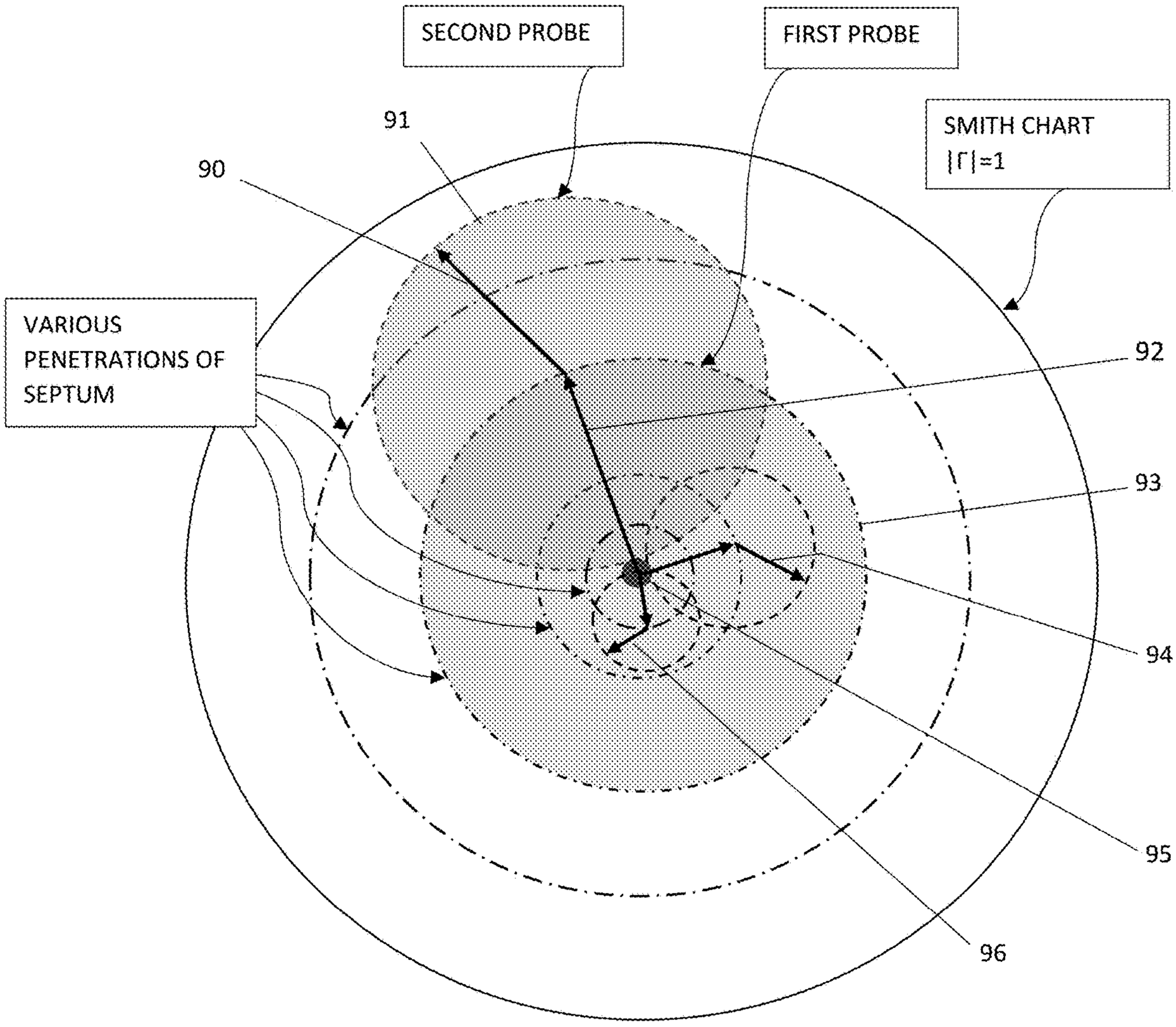

SECOND PROBE
FIRST PROBE
SMITH CHART
|Γ|=1
91
90
VARIOUS
PENETRATIONS OF
SEPTUM
92
93
94
95
96

FIG. 9

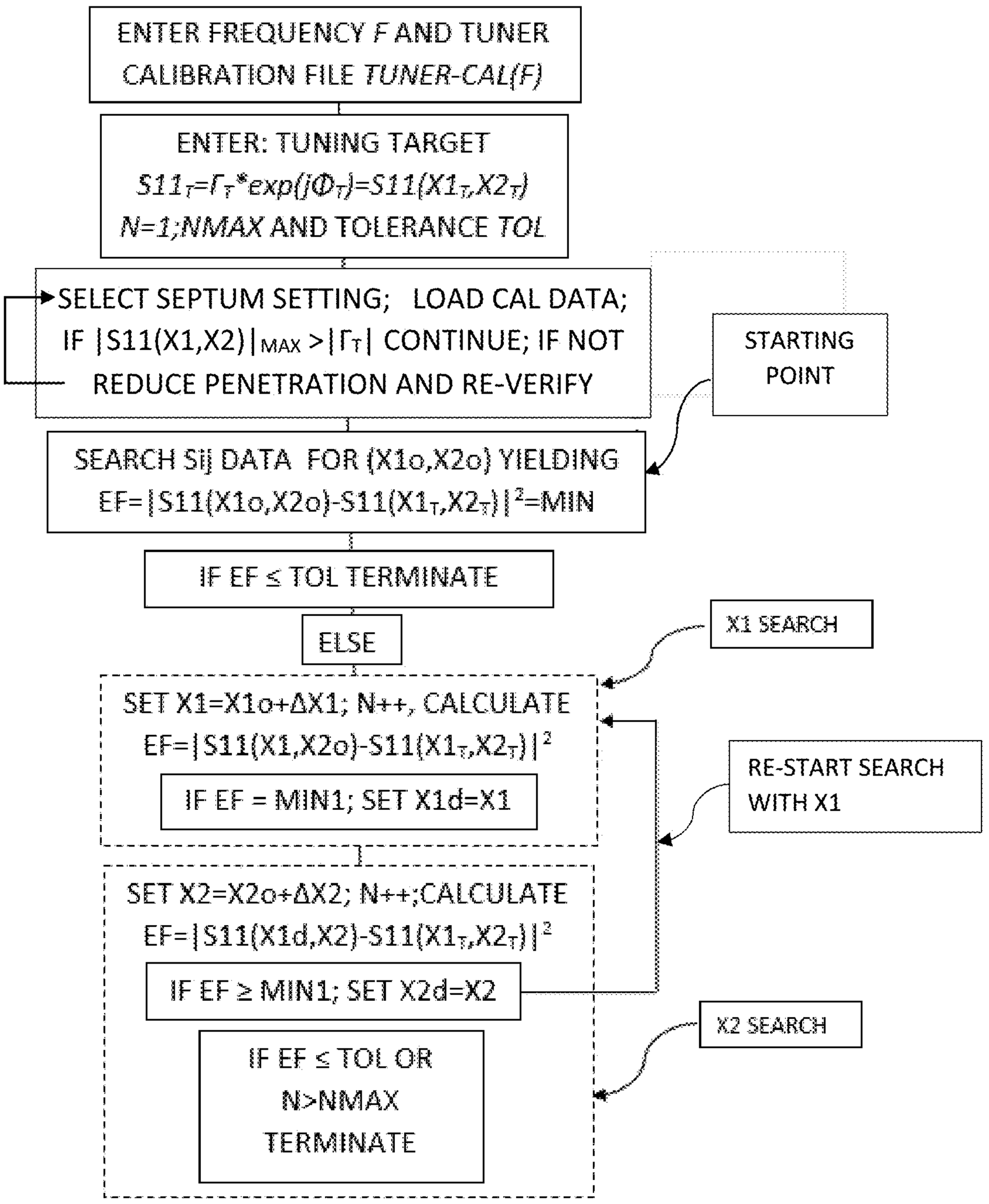

ENTER FREQUENCY F AND TUNER CALIBRATION FILE TUNER-CAL(F)
ENTER: TUNING TARGET
S11T=ΓT*exp(jΦT)=S11(X1T,X2T)
N=1;NMAX AND TOLERANCE TOL
SELECT SEPTUM SETTING; LOAD CAL DATA;
IF |S11(X1,X2)|MAX >|ΓT| CONTINUE; IF NOT
REDUCE PENETRATION AND RE-VERIFY
STARTING POINT
SEARCH Sij DATA FOR (X1o,X2o) YIELDING
EF=|S11(X1o,X2o)-S11(X1T,X2T)|2=MIN
IF EF ≤ TOL TERMINATE
ELSE
X1 SEARCH
SET X1=X1o+ΔX1; N++, CALCULATE
EF=|S11(X1,X2o)-S11(X1T,X2T)|2
IF EF = MIN1; SET X1d=X1
RE-START SEARCH WITH X1
SET X2=X2o+ΔX2; N++;CALCULATE
EF=|S11(X1d,X2)-S11(X1T,X2T)|2
IF EF ≥ MIN1; SET X2d=X2
X2 SEARCH
IF EF ≤ TOL OR
N>NMAX
TERMINATE

FIG. 10

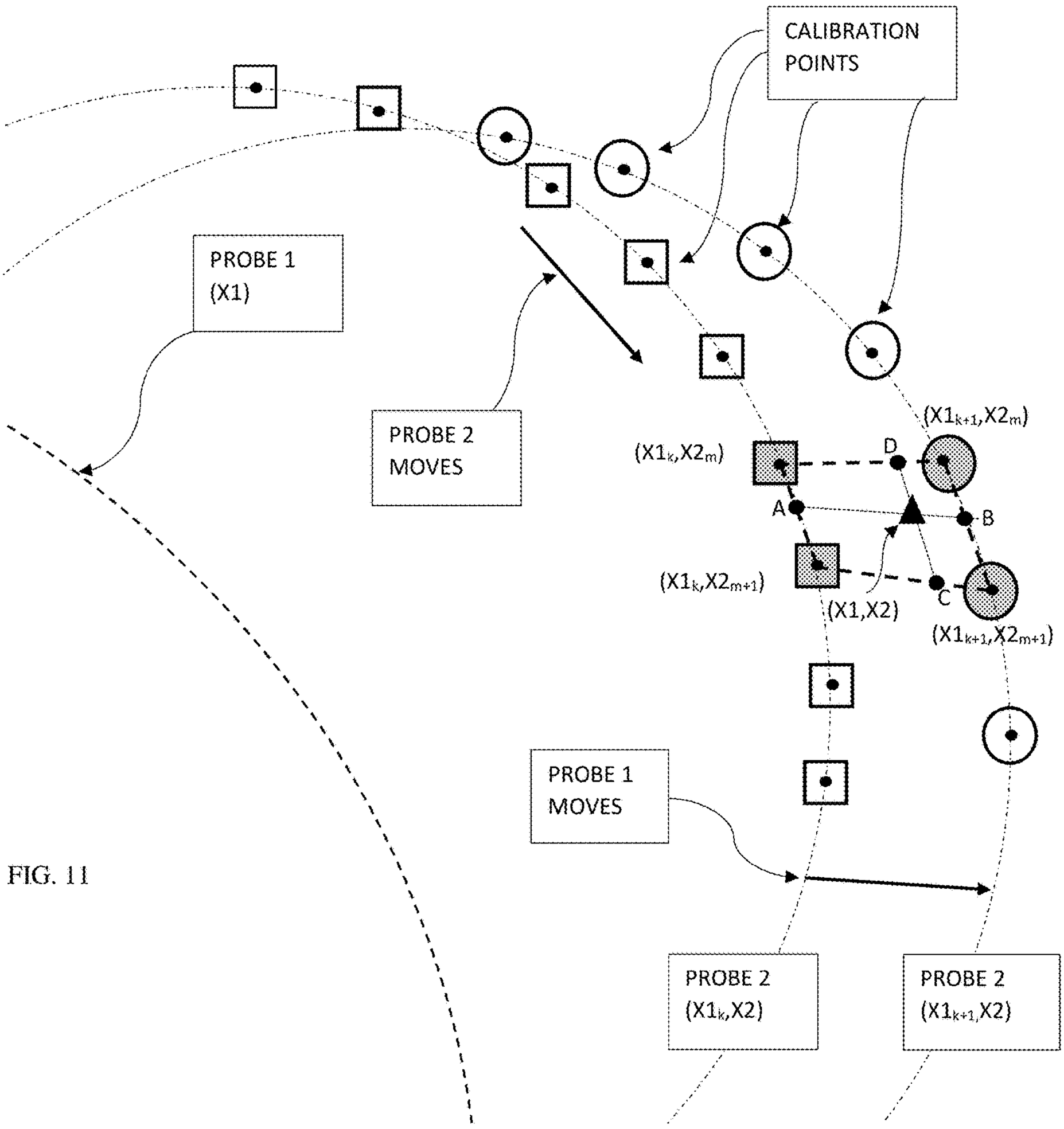

CALIBRATION POINTS
PROBE 1 (X1)
PROBE 2 MOVES
$(X1_{k+1},X2_m)$
$(X1_k,X2_m)$
D
A
B
$(X1_k,X2_{m+1})$
C
(X1,X2)
$(X1_{k+1},X2_{m+1})$
PROBE 1 MOVES
PROBE 2 ($X1_k$,X2)
PROBE 2 ($X1_{k+1}$,X2)

FIG. 11

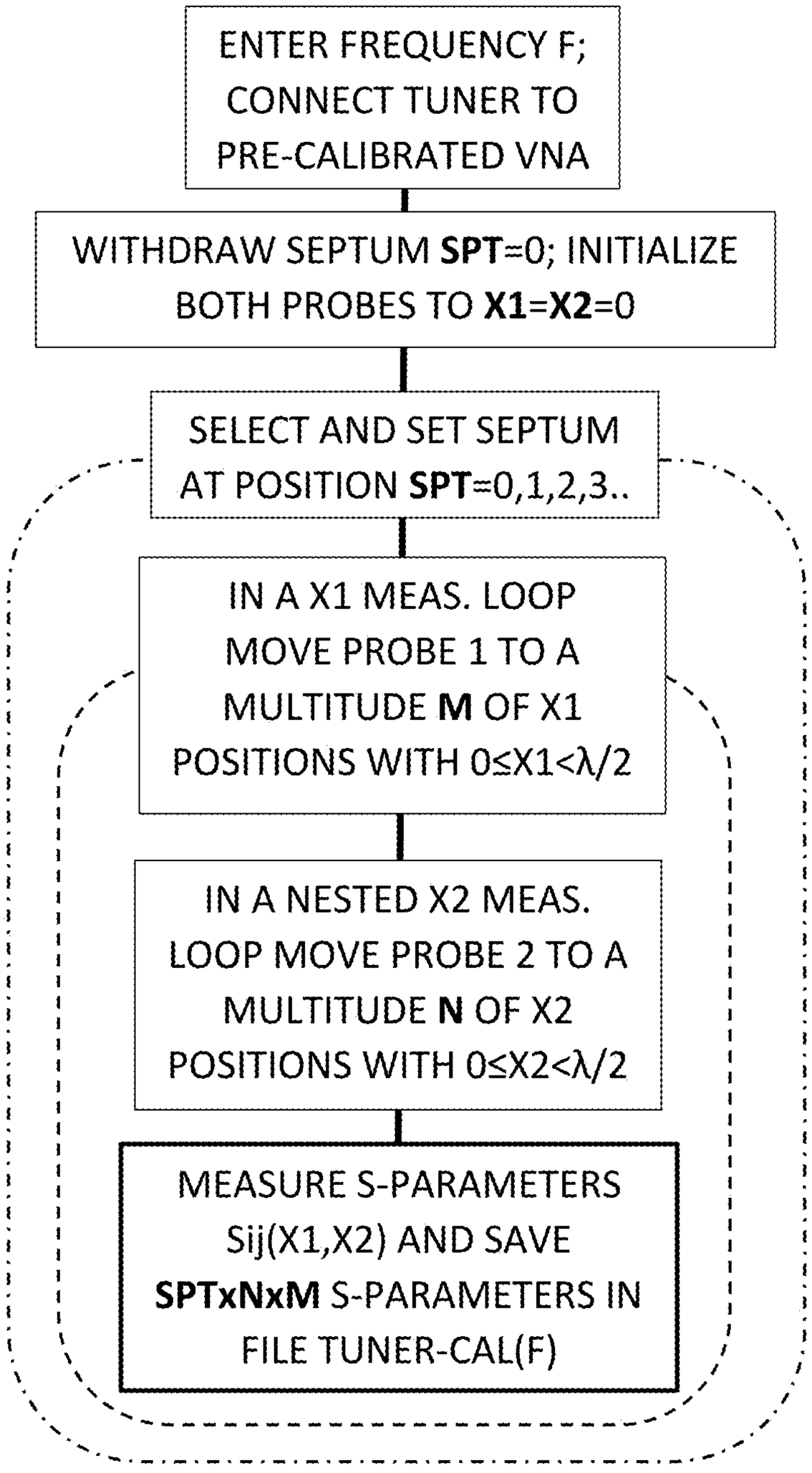

ENTER FREQUENCY F; CONNECT TUNER TO PRE-CALIBRATED VNA
WITHDRAW SEPTUM SPT=0; INITIALIZE BOTH PROBES TO X1=X2=0
SELECT AND SET SEPTUM AT POSITION SPT=0,1,2,3..
IN A X1 MEAS. LOOP MOVE PROBE 1 TO A MULTITUDE M OF X1 POSITIONS WITH 0≤X1<λ/2
IN A NESTED X2 MEAS. LOOP MOVE PROBE 2 TO A MULTITUDE N OF X2 POSITIONS WITH 0≤X2<λ/2
MEASURE S-PARAMETERS Sij(X1,X2) AND SAVE SPTxNxM S-PARAMETERS IN FILE TUNER-CAL(F)

FIG.12

FIG. 13A: Prior art

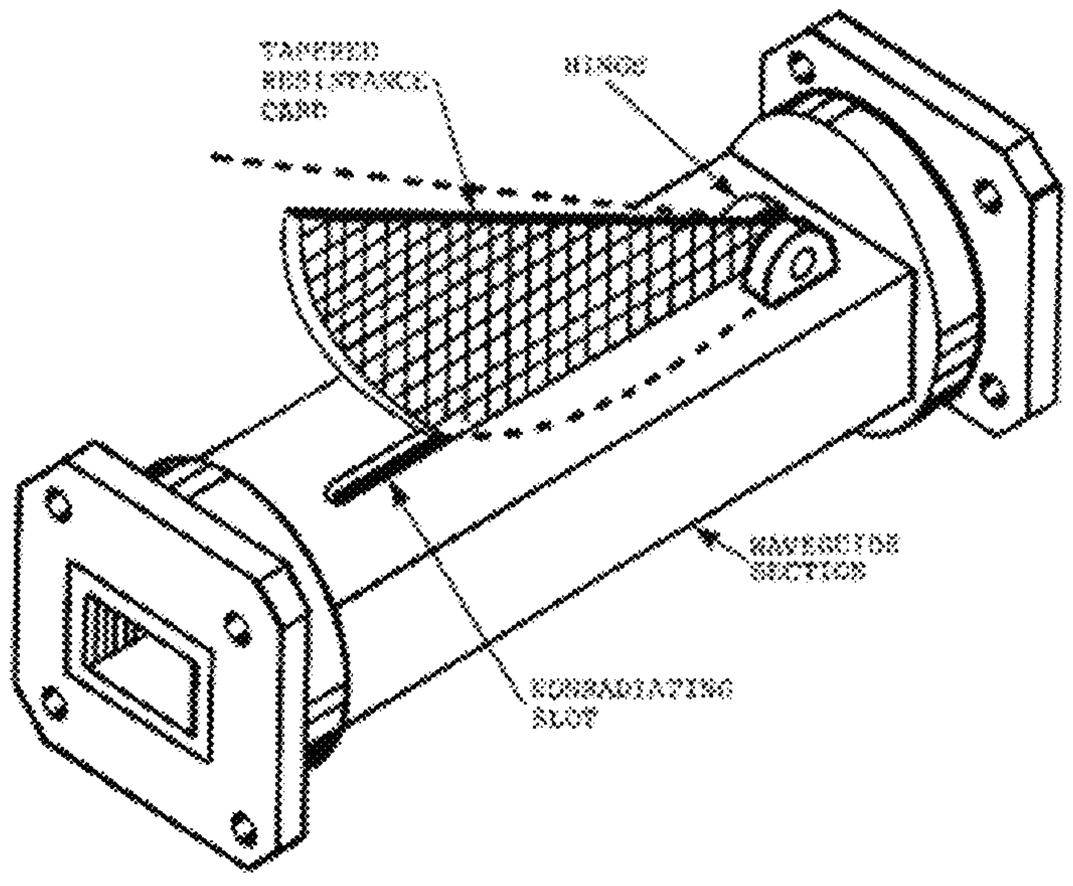
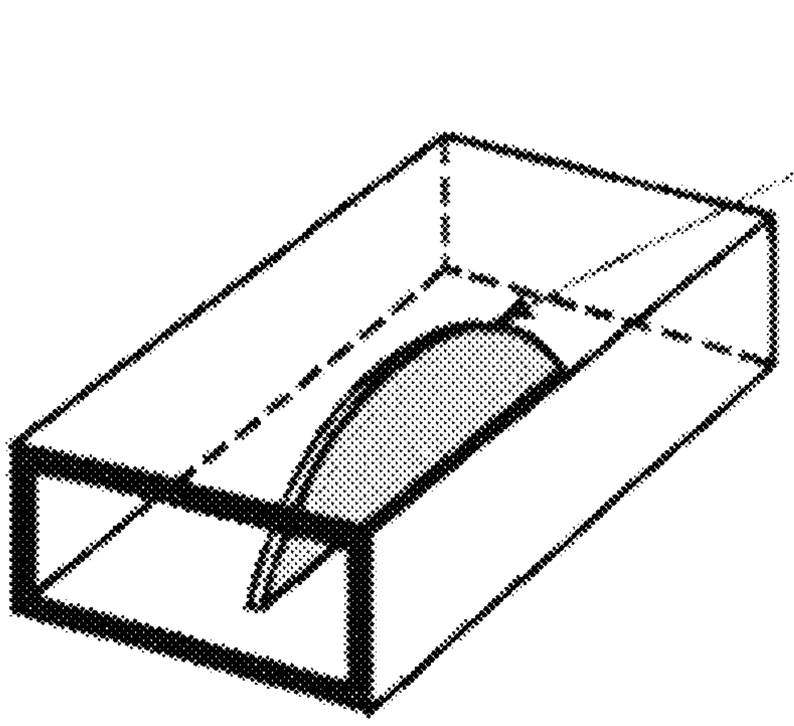


FIG. 13B: Prior art



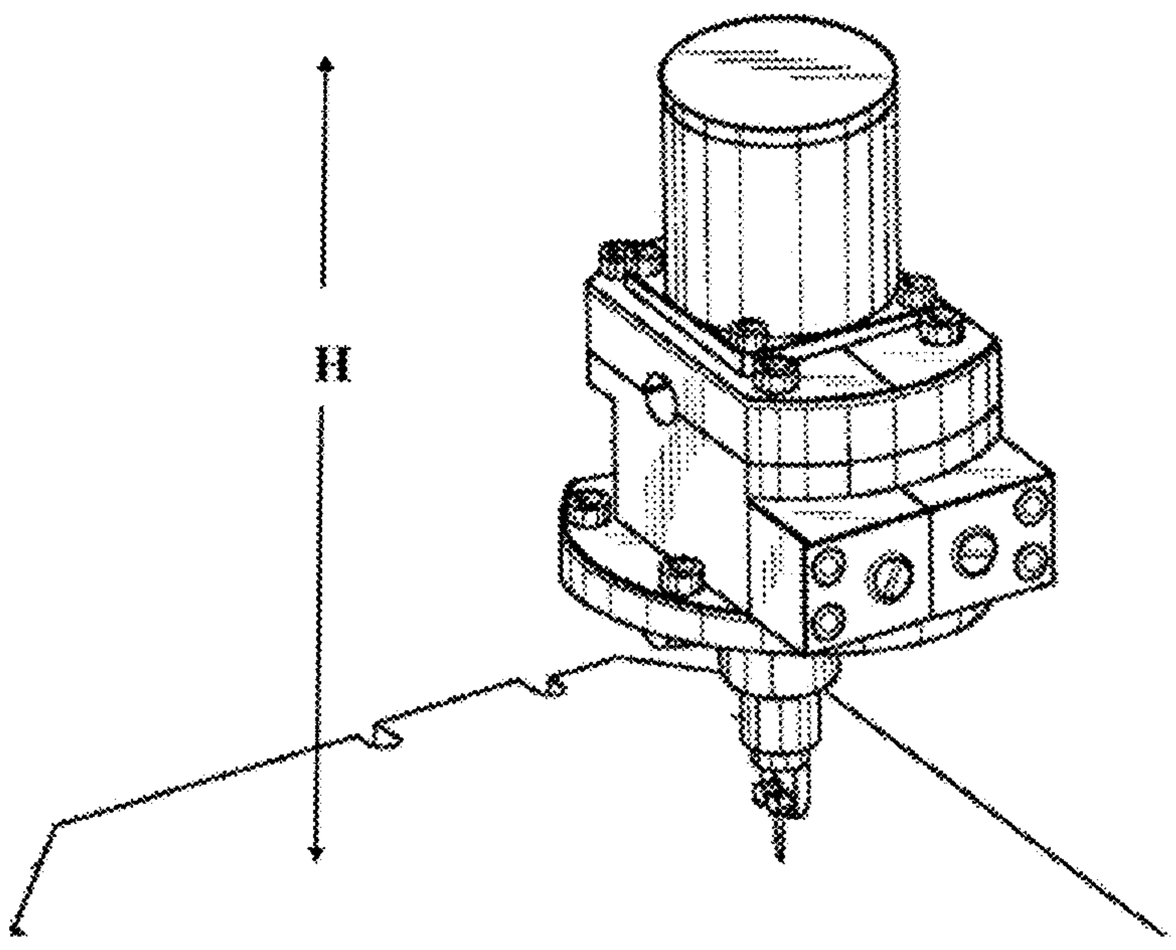


FIG. 14: Prior art

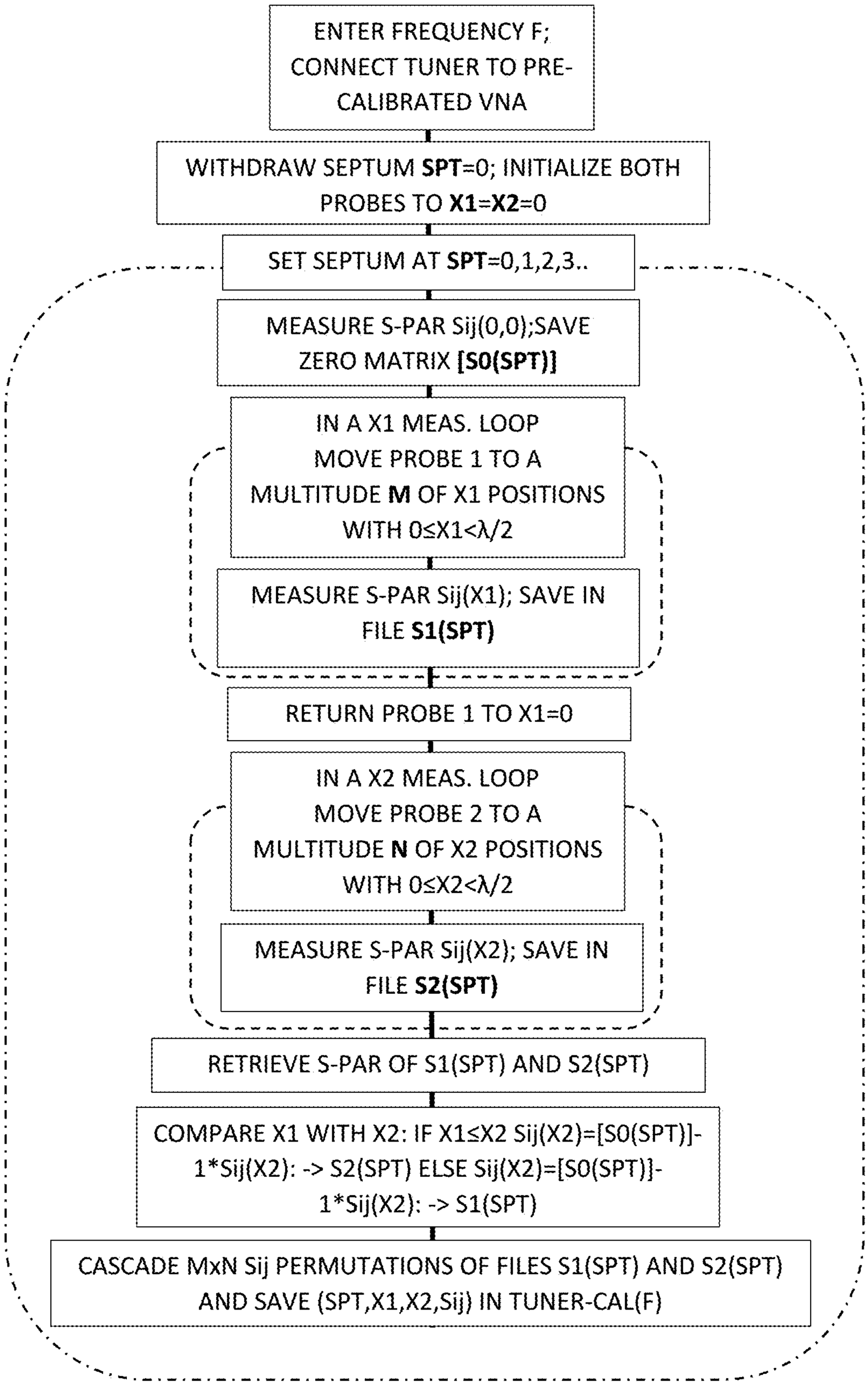

ENTER FREQUENCY F; CONNECT TUNER TO PRE-CALIBRATED VNA
WITHDRAW SEPTUM SPT=0; INITIALIZE BOTH PROBES TO X1=X2=0
SET SEPTUM AT SPT=0,1,2,3..
MEASURE S-PAR Sij(0,0);SAVE ZERO MATRIX [S0(SPT)]
IN A X1 MEAS. LOOP MOVE PROBE 1 TO A MULTITUDE M OF X1 POSITIONS WITH 0≤X1<λ/2
MEASURE S-PAR Sij(X1); SAVE IN FILE S1(SPT)
RETURN PROBE 1 TO X1=0
IN A X2 MEAS. LOOP MOVE PROBE 2 TO A MULTITUDE N OF X2 POSITIONS WITH 0≤X2<λ/2
MEASURE S-PAR Sij(X2); SAVE IN FILE S2(SPT)
RETRIEVE S-PAR OF S1(SPT) AND S2(SPT)
COMPARE X1 WITH X2: IF X1≤X2 Sij(X2)=[S0(SPT)]-1*Sij(X2): -> S2(SPT) ELSE Sij(X2)=[S0(SPT)]-1*Sij(X2): -> S1(SPT)
CASCADE MxN Sij PERMUTATIONS OF FILES S1(SPT) AND S2(SPT) AND SAVE (SPT,X1,X2,Sij) IN TUNER-CAL(F)

FIG. 15

LOAD PULL SYSTEM USING TWO-PROBE WAVEGUIDE TUNER

CROSS-REFERENCE TO RELATED ARTICLES

1. "Load Pull Measurements" [online], Wikipedia [retrieved on Nov. 18, 2016] Retrieved from Internet < URL: en.wikipedia.org/wiki/Load_ pull.>

2. W Band Programmable Tuner Model 11075, Product Note 43, Focus Microwaves August 1977.

3. Simpson et al., U.S. Pat. No. 5,910,754, "Reduced height waveguide tuner for impedance matching", FIG. **8**.

4. Tsironis C., U.S. Pat. No. 6,674,293, "Adaptable Pre-Matched Tuner System and Method".

5. Tsironis C., U.S. Pat. No. 9,625,556, "Method for Calibration and Tuning with Impedance Tuners".

6. "Signal-flow graph" [online], Wikipedia [retrieved on Aug. 31, 2021]. Retrieved from Internet <URL: en.wikipedia.org/wiki/Signal-flow_graph.>

7. "Linear Actuator" [online], Wikipedia [retrieved on Apr. 25, 2020] Retrieved from Internet <URL: en.wikipedia.org/wiki/Linear_actuator>.

BACKGROUND OF THE INVENTION

This invention relates to load and source pull testing of RF and millimeter-wave transistors and amplifiers using remotely controlled electro-mechanical waveguide impedance tuners.

A popular method for testing and characterizing RF and millimeter-wave transistors in their non-linear region of operation is "load pull" (see ref. 1). Load pull is a device measurement technique employing microwave and millimeter-wave impedance (load-pull) tuners and other test equipment as shown in FIG. **1**. The waveguide tuners **2**, **4** (see ref. 2) are used in order to manipulate the microwave impedance conditions under which the Device Under Test (DUT, or transistor, **3**) is tested; the test signal is provided by a signal source **1** and the out-coming power is measured by a power meter **5**; the whole is controlled by a PC controller **6**, which includes an electronic interface to communicate with the instruments **1**, **5** and the tuners **2**, **4** using digital control and communication cables **7**, **8** and **9**.

DESCRIPTION OF PRIOR ART

Waveguide impedance tuners include, in general, a low-loss transmission line **26**, FIG. **2**, and a conductive tuning element (tuning probe, **20**) inserted in a slot **28** machined into the waveguide **23**; the probe **20** is a conductive rod and is attached to a complex, adjustable high precision motor-controlled **25** vertical axis **22** and is inserted contactless **21** into the slot **28** and moved **24** along the axis of the waveguide; this movement of the tuning probe creates, in a certain frequency range, a controllable variable reactance which, combined with a following matched load allow the synthesis of various impedances (or reflection factors) which are present at the test port **27** covering up to the quasi totality of the Smith chart (the polar impedance mapping display shown as normalized reflection factor, FIG. **3**). The impedance synthesis generated by the movement of the tuning probe follows a path **30**, **31** between the matched load at the origin (50Ω) and an arbitrary target-**1**. Inserting the tuning probe into the slot creates path **30** and moving it along the slot creates path **31**. The relation between reflection factor Γ and impedance Z is given by $\Gamma=(Z-Zo)/(Z+Zo)$, wherein

$Z=R+jX$ and wherein Zo is the characteristic impedance. A typical value used for Zo is 50Ω.

When conductive tuning probes (typically, but not exclusively, metallic or metallized rods) **20**, FIG. **2**, penetrate into the waveguide cavity **26**, they capture and deform the electric field, which is concentrated in the area **29** between the bottom tip of the probe **20** and the ground plane **23** of the waveguide. This field deformation allows creating the high and controllable reflection factors. The main disadvantage of this embodiment is the requirement for high precision and resolution and, by consequence, tall and cumbersome vertical probe movement mechanisms **22** (FIG. **14**, see ref. 3) precise over their entire travel range and able to fully insert or extract the tuning probe from the waveguide cavity, since the significant portion of reflection occurs when the probe tip is very close to the inner wall of the waveguide (ground plane). This movement process slows down the tuning procedure for two reasons: (a) when the probe is withdrawn, the vertical movement is lengthy and much less effective in terms of generating useful reflection factor, and (b), because the vertical moving resolution is constant, enhanced positioning accuracy and resolution are required all the way due to high tuning sensitivity in the high reflection area, when the probe is deeply inserted and close to the ground plane.

Related prior art (see ref. 4), both with coaxial or waveguide transmission lines, does not teach impedance tuners with fixed penetration (or vertical position) dual tuning probes; prior art tuners require at least one high precision complex vertical axis (FIG. **14**) to be able to create path **30** in FIG. **3** and tune. Neither relevant prior art ref. 2 or 4 teach a compact tuner using alternatively swapping and crossing over tuning probes in a shared transmission line arrangement. This overlapping structure, though, is essential and compatible with the proposed low profile, compact size tuner and attractive, because of the new high speed adaptive tuner operation (see ref. 4).

BRIEF SUMMARY OF THE INVENTION

The invention discloses a new type waveguide load pull slide screw tuner system. The tuner configuration and the associated calibration and tuning algorithms are different from prior art; the tuner uses horizontal-only high-speed movement techniques of two crossing over tuning probes (conductive rods) penetrating in slots of the waveguide and an integrated damping attenuator allowing the control of the wideband reflection factor.

In order to allow the tuning rods to cross over without mechanical conflict, the slots are slightly offset from the center line of the waveguide, by at least one diameter (thickness) of a tuning rod. A medium size reflection ($S11\approx0.5-0.7$) is created by either tuning rod leading to a new tuning mechanism as shown in FIG. **3** (traces **32**, **33**). The tuning mechanisms following prior art path **30-31** and new paths **32-33** and **34-35** shown in FIG. **3**, all yield the same result: starting from the matched load (50Ω) they allow tuning to targets **1** to **3**. The result is the same, only the control mechanisms differ. However new path **32-33** can tune to 50Ω only at a concrete frequency, there is always a high reflection at another frequency range, which may cause spurious oscillations of the DUT; however, inserting the resistive tapered septum **55**, limits the maximum reflection at all frequencies (path **34-35**).

The probe holding carriages **45** are controlled using high-speed electric stepper motors **54** and ACME rods **51** or actuators (see ref. 7), thus eliminating this way additional control gear. Last, not least, the tuning mechanism, liberated

from cumbersome and expensive high resolution vertical probe control and movement delays, benefits also from inherent lower tuning error sensitivity to mechanical probe positioning tolerances close to $|\Gamma|\approx 1$.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The invention and its mode of operation will be better understood from the following detailed description when read with the appended drawings, in which:

FIG. **1** depicts prior art: a typical generic automated load pull test system.

FIGS. **2**A through **2**B depict prior art: a single probe waveguide impedance tuner; FIG. **2**A depicts a front view of the entire tuner; FIG. **2**B depicts a cross section of the tuning probe (typically a conductive rod) entering the waveguide slot.

FIG. **3** depicts partly prior art: a Smith chart and three possible trajectories of impedance synthesis (tuning) to reach target impedances, starting from the origin of 50Ω. Reaching target-**1** uses the prior art single-probe technique with horizontal and vertical tuning probe control; reaching targets **2** and **3** uses the new two-probe technique with horizontal only and without vertical control. Target-**2** is reached without septum attenuation, target-**3** with moderate septum attenuation (see also FIG. **14**).

FIG. **4** depicts a cross-section through a waveguide transmission line with two conductive tuning rods (probes) entering from opposite sides into slightly offset slots.

FIG. **5** depicts a front view of the waveguide tuner with two crossing over tuning probes and a resistive tapered attenuation septum.

FIGS. **6**A through **6**D depict the signal flow graph (SFG, see ref. 6) of the two-probe impedance tuner with resistive tapered septum attenuator: FIG. **6**A depicts the equivalent circuit of the septum attenuator; FIG. **6**B depicts the overall signal flow graph; FIG. **6**C identifies the signal transmission flow and nodes of the tuner depicted in the signal flow graph and FIG. **6**D depicts the reflection area of a tuning probe.

FIG. **7** depicts signal flow and multiple reflections created by the two probes and the resistive tapered septum of a two-probe impedance tuner with shared waveguide. The probes can swap positions with regard to the test port **70**.

FIG. **8** depicts the Smith chart coverage mechanism using two-probe impedance tuner with fixed probe insertion depth with the resistive septum withdrawn.

FIG. **9** depicts the Smith chart coverage, created using the two-probe impedance tuner with fixed probe insertion depth and a set of resistive septum insertions.

FIG. **10** depicts the impedance synthesis (tuning) flowchart.

FIG. **11** depicts the interpolation technique.

FIG. **12** depicts a ("brute force"=full permutation) calibration flowchart.

FIGS. **13**A through **13**B depict prior art: embodiments of resistive attenuation cords or septum.

FIG. **14** depicts prior art: a cumbersome vertical axis used in a waveguide tuner (see ref. 3).

FIG. **15** depicts the flowchart of the fast de-embedding tuner calibration.

DETAILED DESCRIPTION OF THE INVENTION

This invention discloses a high frequency (RF, microwave, millimeter wave), computer-controlled impedance tuning system, suitable for load pull measurements, which includes at least one electro-mechanical waveguide impedance tuner, the calibration method of the tuner and an impedance synthesis (tuning) method. The tuner (FIGS. **4** and **5**) uses a low loss waveguide transmission airline **40**, which includes two broad top walls, two narrow sidewalls and three slots: two slots **46** and **47** and one slot **56** cut into the broad walls: two slots (**47** and **56**) are cut on the top and one slot **46** is cut on the bottom wall. All slots run parallel **43** to the waveguide longitudinal axis and the slots **46** and **47** are positioned opposite to each other and slightly offset from the symmetrical center line of the waveguide. The offset dimension is selected to allow two tuning probes (typically metallic or metallized rods **42**) to cross over without touching. This structure is chosen for economy of space, because it uses slots of a total length of one half of a wavelength plus the thickness of one tuning rod, so there is a $\lambda/2$ free travel possible in order to cover 360° reflection factor angle. An alternative configuration, where the tuning rods would not cross over, would, in principle, also work, but the slot (and the tuner) would have to be twice as long. The horizontal control of the carriages **45** can be accomplished using stepper motors **54** and ACME **51** screws as well as linear electric actuators (see ref. 6). The actuators have a motorized body, and their rotor axis is the extended horizontal ACME screw **51**.

The tuner also includes a tapered resistive septum **55**, insertable into the third slot between the test port **50** and the tuning probes **42**; the septum is inserted in the third slot on one of the broad waveguide walls and serves in damping the signal flow (FIG. **13**A and **13**B). The tuner having two non-withdrawable tuning probes can only tune to 50Ω at one frequency; everywhere else the residual reflection can be high, in which case the DUT may oscillate triggered either by the stimulus signal or spontaneously at random, in particular at low frequencies where the DUT gain is typically high, and render the measurement meaningless; to avoid such a situation the resistive septum, in reality an adjustable wideband low reflection attenuator, is inserted and limits the range of reflection (FIG. **9**); the setting of the septum is selected to a few values SPT (penetrations) and is part of the tuner calibration and is used accordingly. If the DUT is absolute stable the septum is fully withdrawn (SPT=0) and the attenuation is negligible.

FIG. **5** shows a front view of the waveguide tuner also shown as a cross section **41**, **44** of FIG. **4**: the opposite slots **46** and **47** can be seen to be half a wavelength long and **56** being as long as the resistive tapered septum **55** requires, which is inserted into the cavity **26** of the waveguide rotated by remotely controlled motor **57**; the mobile carriages **45** are controlled by the ACME screw **51** along the waveguide via the stepper motors **54**; the reference position of one carriage/probe is X**1** and of the other is X**2**, both relative to an arbitrary, but common, zero position. The electric distance of the first tuning rod **42** from the test port **50** is L**1** and the electric distance between the two tuning rods is L**2**; the lower slot **46** is partially hidden in FIG. **5** as it is evident from the cross section **44** in FIG. **4**.

The signal propagation paths are shown in FIG. **7**: the total controlled reflection factor **S11**(X**1**,X**2**) **70** is a dynamic function of the combined positions X**1** and X**2** of the two probes **76** and **77** and the static setting of the resistive septum **702**; the dynamic reflection is the vector-sum of the static vector **703** and the dynamic reflection factors **71** and **72** of both probes **S11**(X**1**)+**S11**(X**2**): **S11**(X**1**,X**2**)=**S11**(X**1**)+**S11**(X**2**), all referenced at the test port **70**. The resistive septum **702** adds the small static reflection **703**, but its

main function is wideband signal attenuation, in order to reduce the risk of spontaneous spurious oscillations of the DUT. The signal **705** passing through the attenuator **702** reaches the tuning probe **76** closest to the test port generates the primary reflection **71**; this returning signal is split by the attenuator **702** into a traversing portion **706** and a reflected portion **704**. Since this reflection is selected not to be total, there is a signal portion **74** traversing towards the secondary probe **77**; this signal portion is then reflected back **72** towards the primary probe; again, a portion **75** of this reflected back signal traverses the primary probe **76** towards the test port and adds to the total reflection **70**. The signal **72** reflected at the secondary probe is also reflected back **73** at the primary probe, and so on, creating the phenomenon of a multiple reflection. In mechanical (aero-dynamics, hydraulics) terms this appears like a turbulence. This back and forth bouncing of signal is described using signal flow graphs (see ref. 5). Instead, since the tuner is terminated with a matched load any escaping signal **78** is not reflected back **79** and is therefore ignored. A similar phenomenon occurs between the resistive tapered septum **702** and probe **76**, creating an additional set of multiple reflections **704-71**.

FIG. **6**B shows the signal flow graph describing the tuner, which is also shown schematically in FIG. **6**C: Each pair of nodes represents a port and each branch the complex signal flow s-parameter S**11** or S**21**; each tuning probe (FIG. **6**D) is described by a two-port having a reflection factor R (S**11**, S**22**) and a transmission factor T (S**21**, S**12**): probe **1** has R**1** and T**1**, probe **2** has R**2** and T**2** and the resistive septum (FIG. **6**A) has a small residual reflection R**0** and a controlled attenuation T**0**. The injected signal <a> returns as <b> after traversing several simple and revolving loops. The simple loops describe direct reflections and the revolving loops the multiple reflections: loops **1**, **2** and **5** are direct (simple) loops and loops **3**, **4** and **6** are revolving loops. Direct loops contribute single vector components to the returning signal wave <b>. Revolving loops contribute an infinite series of rapidly vanishing signal wave vectors. The total sum is therefore converging. Between each probe there is a delay $\exp(-j\beta L)$; transmission lines are described by simple phase delays $\beta 1=2\pi L1/\lambda$ or $\beta 2=2\pi L2/\lambda$. Assuming the probes represent capacitors C=C**1** and C=C**2** (FIG. **6**D) then we can approximate: $R1=-j\omega C1Zo/(2+j\omega C1Zo)$; $R2=-j\omega C2Zo/(2+j\omega C1Zo)$; $T1=2/(j\omega C1Zo)$ and $T2=2/(2+j\omega C2Zo)$. In the case of the resistive septum (FIG. **6**A) we get: $R0=Zoj\omega C/(2R+Zo)j\omega C+2)$ and $T0=2(Rj\omega C+1)/(j\omega C(Zo+2R)+2))$; The section after probe **2** is 50Ω, therefore signal is not returning and the associated T**2** is ignored. By generating the signal loops **1**, **2**, **3**, . . . which contribute to the overall reflected signal <b> we obtain for the reflection factor at the test port:

$$S11=<b>/<a>\approx\{-R0-e^{-j2\beta L1}T0^2R1-e^{-j2\beta(L1+L2)}R2T1^2T0^2-e^{-j2\beta(L1+2L2)}T1^2T0^2R2^2R1-e^{2\beta(L1+2L2)}R2T1^2T0^2R0R1\ldots\};$$

the series of loops is truncated, since the loops **3**, **4** and **6** are repeated n times with n=1,2,3,4 . . . towards infinite, but their contribution to the total reflection factor at the test port is rapidly decreasing, since all s-parameters R (reflection) and T (transmission) and their products appearing at higher power $T0^{2n}$, $T1^{4n}$, $R0^{2n}$, $R1^{2n}$, $R2^{4n}$ etc. are geometrically smaller than 1, forming this way a converging infinite sum. The transmission between the test port **70**, probe **1**, **73** and probe **2**, **77** is described by lossless transmission lines having a phase $-2\pi L/\lambda$, where λ is the wavelength λ=300 mm/Frequency(GHz).

Coverage of the Smith chart is shown in FIG. **8**: Overall S**11**(X**1**,X**2**) **105** is created by vector sum of S**11**(X**1**) **103** and S**11**(X**2**) **104**; the canter of the Smith chart **102** is reached when S**11**(X**1**) and S**11**(X**2**) are opposed and a maximum when they are in line (same phase). Movement X**1** created a circle **100** and movement X**2** an epicycloid trajectory **101**.

The effect of the attenuator **702** is shown in FIG. **9**: at low septum penetration we observe vectors **90**, **92** on trajectory **93** around the center **95** synthesizing trajectory **91**; at medium septum penetration we observe vector **94** and at high penetration vector **96**.

The tuner calibration process at a given frequency F has been reported before for single or multiple probe tuners with vertical probe control (see ref. 5); in the present case of horizontal only probe control, calibration is possible using a traditional method (FIG. **12**) consisting in measuring, on a pre-calibrated vector network analyzer (VNA) s-parameters between the test **70** and idle **701** ports (FIG. **7**) for a limited number of resistive septum settings SPT (FIG. **9**): all N*M permutations of 1,2,3 . . . N times X**1** and 1,2,3 . . . M times X**2** tuning probe positions are measured with typical SPT settings of 2 or 3 and N~M values of at least 100, in order to generate a dense enough grid of calibrated points of no more than 3.6° angle between points on the Smith chart. In this case the total calibration of 10,000 points for one SPT setting will last an average of 2.5 hours (assuming 1 second per point, including probe movement, data collection and saving).

The preferred embodiment of a de-embedding calibration method of the actual tuning section after the resistive septum allows a much faster operation as follows (FIG. **15**): measure first the s-parameters of the waveguide transmission line with both probes initialized (X**1**=X**2**=0) and the septum pre-set to one of the pre-selected states SPT (SPT=0 means septum is withdrawn, medium insertion, stronger insertion etc . . .) and save in a zero matrix [S**0**(SPT)]; then move probe **1** to a multitude of M positions X**1** and measure s-parameters Sij(X**1**) between the test and idle ports of the tuner and save the data in a file S**1**(SPT); then initialize probe **1** to X**1**=0, move probe **2** to a multitude N positions X**2**, measure s-parameters Sij(X**2**) and save in a file S**2**(SPT). Subsequently the data in files S**1**(SPT) and S**2**(SPT) are retrieved and saved in rapid access memory RAM of the system controller; since the probes may cross over each other, X**1** can be equal, bigger or smaller than X**2** and this decides on the sequence of de-embedding: if X**1**≤X**2**, then Sij(X**2**) is de-embedded, i.e., cascaded with $[S0(SPT)]^{-1}$ and re-saved in file S**2**(SPT); else, if X**1**>X**2**, then Sij(X**1**) is de-embedded, i.e., cascaded with $[S0(SPT)]^{-1}$ and re-saved in file S**1**(SPT); subsequently all M*N permutations of the s-parameters in updated files S**1**(SPT) and S**2**(SPT) saved in RAM, are cascaded into a new set of M*N s-parameter sets Sij(X**1**,X**2**) which are the calibration data of the tuner at frequency F for the given SPT: TUNER-CAL(F); the data in the tuner calibration file are sorted in SPT blocks, i.e., for each SPT value 0, 1, 2, 3 . . . there is a block of N*M Sij(X**1**,X**2**) data sets; presumably all s-parameter matrix cascading is executed after converting s-parameters to ABCD or transfer (T-parameters), and back to s-parameters; the result of this operation lasts much less than before: a total of M+N points per SPT setting are measured and data are processed very fast in memory. The total time for each septum setting (assuming 1 second per point, as before) is: 200*1 sec+20 sec (processing time)≈4 minutes, compared with approximately 2.5 hours, a significant gain.

In order to synthesize a large number of possible target impedances using a limited number of calibration data

requires adequate interpolation routines, because the tuner has millions of possible states (depending on the frequency and step resolution of the carriage control, the probes can be set to 1000 or more distinct X1 and X2 positions or motor-steps, in which case we have 1 million or more distinct tunable impedances). The interpolation routine uses the points on the two trajectories shown in FIG. **11**; the high number of interpolated points allows accurate determination of the s-parameters Sij(X1,X2) of the tuner for any arbitrary probe settings (X1,X2) of the tuning probes at the pre-selected SPT setting, based on the four closest calibration points ($X1_k$,$X2_m$), ($X1_{k+1}$,$X2_{m+1}$), ($X1_{k+1}$,$X2_m$) and ($X1_k$, $X2_{m+1}$), each pair selected on either the X1 or the X2 direction or trace of probe movement (FIG. **11**); herein the probe positions are selected to be successive: $X1_k \le X1 < X1_{k+1}$ (on the X1 trace) and $X2_m \le X2 < X2_{m+1}$ (on the X2 trace), in order to create a polygon between the above calibrated points, that includes the tunable point with target coordinates (X1,X2); once these four points are determined, the interpolation executes in two steps: in step 1 linear interpolation allows determining s-parameters of four new interpolated points, marked in FIG. **10** as A, B, C, D: as follows:

$$Sij(A)=Sij(X1_k,X2_m)+(X2-X2_m)/(X2_{m+1}-X2_m)\cdot(Sij(X1_k,X2_{m+1})-Sij(X1_k,X2_m)); \quad [eq.\ 1]$$

$$Sij(B)=Sij(X1_k,X2_m)+(X2-X2_m)/(X2_{m+1}-X2_m)\cdot(Sij(X1_{k+1},X2_{m+1})-Sij(X1_{k+1},X2_m)); \quad [eq.2]$$

$$Sij(C)=Sij(X1_k,X2_{m+1})+(X1-X1_k)/(X1_{k+1}-X1_k)\cdot(Sij(X1_{k+1},X2_{m+1})-Sij(X1_k,X2_{m+1})); \quad [eq.3]$$

$$Sij(D)=Sij(X1_k,X2_m)+(X1-X1_k)/(X1_{k+1}-X1_k)\cdot(Sij(X1_{k+1},X2_m)-Sij(X1_k,X2_m)); \quad [eq.4]$$

In step 2 then, a new linear interpolation generates Sij(X1, X2) using these four new first order interpolated points Sij(A), Sij(B), Sij(C) and Sij(D) as follows:

$$Sij(X1,X2)=\{Sij(A)+(X1-X1_k)/(X1_{k+1}-X1_k)\cdot(Sij(B)-Sij(A))+Sij(C)+(X2-X2_{m+1})/(X2_m-X2_{m+1})\cdot(Sij(C)-Sij(D))\}/2. \quad [eq.5]$$

Once the tuner is calibrated and the s-parameter data Sij(X1,X2) are saved in a calibration file TUNER-CAL(F) at a frequency F and a number of septum settings SPT, they can be used to synthesize, either manually or in an automatic measurement procedure, user-defined impedances or reflection factors; the tuning process executes in a number of steps (FIG. **10**): in a first step, after the frequency, the number of allowable search iterations NMAX and the tuning tolerance TOL (the allowable vector difference between the target and the tuned reflection factor) are defined, the process starts with the highest SPT setting (deepest septum penetration=largest attenuation) and loads the data of the tuner calibration file in random access (fast) RAM memory. The data are imported from the associated calibration file TUNER-CAL(F) and are scanned for the maximum reflection factor |S11(X1,X2)| which is compared with the target reflection factor $|S11(X1_T,X2_T)|$: if the target vector is larger than the vector of the smallest maximum vector of the calibrated points, then the search returns by reducing the septum penetration (and the attenuation) to the next pre-selected SPT value and re-loads the data. The comparison repeats until a septum setting is determined, which allows the calibrated points to include the target point. Once this initial issue is settled the search starts by comparing the newly downloaded calibrated reflection factors S11(X1,X2) with each imported Γ and determines a set of starting values (X1o,X2o) for which the vector distance in form of an error function $EF=|S11(X1o,X2o)-\Gamma|^2$ is smallest (i.e., finding the smallest vector distance between the target Γ and the closest calibrated point) to be used in the subsequent search.

If this value EF is already smaller than the prescribed tuning tolerance TOL, the X1o,X2o values are saved, and the search terminates with X1.final=X1o and X2.final=X2o. Else, starting with X1o,X2o, the process modifies X1 and X2 alternatively by small amounts δX1 and δX2, which are proportional (in a regula falsi kind of algorithm) to the change of the error function EF, the new interpolated value S11(X1+δX1,X2+δX2) is calculated and EF re-calculated until a new local minimum of EF is reached. This means, if EF increases, then the δX1 or δX2 correction becomes negative and the X1 or X2 search reverses direction. After a first local minimum of EF, the search changes direction, conserves the actual X1 value and changes X2 as before; each time the EF function traverses a local minimum the search switches from X1 to X2 and back. After a number of iterations the vector (X1,X2) converges to final values X1.final and X2.final, either because EF is smaller that the tuning tolerance or the search is truncated, because the previously defined maximum number of iterations NMAX is exceeded. The search may end up in a local minimum with EF larger than the tuning tolerance, though in the case of only two variables a local minimum is improbable; any residual difference would be related to the density of calibrated points or the size of the tuning tolerance (which cannot be zero, since the stepping motor control of the tuning probes dictates that the tuner, even with at very high positioning resolution, because of the use of stepper motors, remains digital). To be able to execute this procedure, requires the accurate interpolation routines described above, i.e., mathematical relations that allow calculating s-parameters Sij of the tuner at arbitrary probe positions (X1,X2) different than the calibrated positions. For best accuracy these relations must describe approximately enough the natural behavior of the tuner as shown in (FIG. **9**).

Obvious alternative embodiments of fixed penetration tuning probes, diametrically inserted into and sharing the same slabline of waveguide slide screw impedance tuners and associated calibration and tuning methods shall not impede on the core idea of the present invention.

What is claimed is:

1. A load pull waveguide tuner comprising:

a1) a waveguide transmission line with two broad walls, a top broad wall, and a bottom broad wall, and two narrow side walls, a test port, and an idle port, three slots, a first, a second and a third slot, parallel to a longitudinal axis of the waveguide transmission line, and two tuning probes, probe P#**1** and probe P#**2** having a thickness; wherein

the first slot is centered on one of the two broad walls and placed between the test port and the second and third slots, the second and third slots are placed one on the top and one on the bottom broad wall, symmetrically off a center line of the waveguide transmission line by at least half the thickness of the tuning probes;

a2) two remotely controlled mobile carriages C#**1** and C#**2**, mounted one on the top and one on the bottom broad wall and moving along the waveguide transmission line; the carriage C#**1** holding the tuning probe P#**1** and the carriage C#**2** holding the tuning probe P#**2**, which said probes are inserted from opposite sides, at a fixed penetration, tuning probe P#**1** into the second slot and tuning probe P#**2** into the third slot, and

a3) a tapered resistive attenuation septum remotely insertable into the first slot; and wherein

the carriage C#**1** moves the probe P#**1** to a position X**1** relative to the test port, and the carriage C#**2** moves the probe P#**2** to a position X**2** relative to the test port.

2. The load pull tuner of claim **1**, wherein

the second and third slots of the waveguide transmission line are at least one half of a wavelength long (λ/2) at a minimum operation frequency (Fmin) of the load pull tuner.

3. A tuner calibration method of the load-pull tuner of claim **2**, comprising the following steps:

connect the load-pull tuner to a vector network analyzer (VNA), pre-calibrated at a frequency F;

define two or more insertion settings (SPT)=0, 1, 2, . . . of the resistive septum;

withdraw the resistive septum from the waveguide transmission line to SPT=0;

in a succession of septum and tuning probe setting and measurement loops proceed as follows:

in a septum setting and measurement loop:

(a) set the septum to a position SPT=0,1,2 . . . :

move the tuning probes to X**1**=X**1**.**0** and X**2**=X**2**.**0** relative to the test port (initialize);

in a set of nested loops:

(b) in a first nested measurement loop for a multitude M>1 of positions X**1**, with X**1**.**0**≤X**1**≤X**1**.**0**+λ(F)/2:

move tuning probe P#**1** to position X**1**, in a second nested measurement loop, inside the first nested loop, for a multitude N>1 of positions X**2** with X**2**.**0**≤X**2**≤X**2**.**0**+λ(F)/2,

move tuning probe P#**2** to position X**2**;

measure s-parameters Sij, whereby {i,j}={1,2};

save (SPT, X**1**, X**2**, Sij(SPT,X**1**,X**2**)) in a file TUNER-CAL(F);

resume to the next step of the first nested loop (b);

when the first nested loop (b) terminates, resume with the septum setting loop (a);

when the septum setting loop (a) terminates, save the file TUNER-CAL(F) and terminate.

4. A tuner calibration method of the load-pull tuner of claim **2**, comprising the following steps:

connect the load-pull tuner to a vector network analyzer (VNA), pre-calibrated at a frequency F;

define two or more insertion settings SPT=0, 1, 2, . . . of the resistive septum;

withdraw the resistive septum from the waveguide transmission line to SPT=0;

move the tuning probes to positions X**1**=X**1**.**0**, X**2**=X**2**.**0** relative to the test port (initialize);

in a septum setting and measurement loop:

set the septum to a position SPT=0,1,2 . . . :

measure s-parameters of the load-pull tuner and save in zero matrices [S0(SPT)];

in a succession of septum and tuning probe settings and measurement loops proceed as follows:

in an overall septum SPT loop:

set the septum to a position SPT=0,1,2 . . . ;

in a first nested measurement loop, set probe P#**1** to a multitude M>1 of positions X**1**, with X**1**.**0**≤X**1**<X**1**.**0**+λ/2, measure s-parameters Sij (X**1**,X**2**.**0**), with {i,j}={1,2} and save in a file S1(SPT);

return probe P#**1** to the position X**1**=X**1**.**0** (initialize);

in a second nested measurement loop, set probe P#**2** to a multitude N>1 of probe P#**2** positions X**2**, with X**2**.**0**≤X**2**<X**2**.**0**+λ/2, measure s-parameters Sij(X**1**.**0**,X**2**), with {i,j}={1,2} and save in a file S2(SPT);

retrieve the s-parameters of the files S**1**(SPT) and S**2**(SPT);

scan the retrieved s-parameters and compare X**1** with X**2**:

if X**1**≤X**2** cascade (convert s-parameters to transfer parameters, multiply and convert back to s-parameters) the s-parameters Sij(X**1**.**0**,X**2**) with $[S0(SPT)]^{-1}$ and replace in the file S2(SPT),

else if X**1**>X**2** cascade the s-parameters Sij(X**1**,X**2**.**0**) with $[S0(SPT)]^{-1}$ and replace in file S1(SPT);

retrieve the s-parameters from the updated files S1(SPT) and S2(SPT), cascade the s-parameters of all permutations N*M in computer memory and save (SPT,X**1**,X**2**,Sij(SPT,X**1**,X**2**)) in file TUNER-CAL(F);

continue with the overall SPT loop.

5. An interpolation method of the load pull tuner as in claim **2** comprising:

a) retrieve septum setting SPT, tuning probe positions X**1** and X**2** and s-parameters Sij(SPT, X**1**,X**2**) of the calibrated points from a tuner calibration file comprising all setting permutations of the septum SPT and the two tuner probes X**1** and X**2** of the tuner and the associated s-parameters;

b) define a target point (X**1**.t,X**2**.t);

c) identify, using a numeric search, two pairs of successive calibration point coordinates, one pair of probe P#**1** setting X**1** and one pair of probe P#**2** setting X**2**, closest to the target point (X**1**.t,X**2**.t);

d) execute a first set of linear interpolations of s-parameters Sij, one interpolation in X**1** settings and one interpolation in X**2** settings between the four closest calibration points, yielding s-parameters Sij at four new points A,B in X**1** setting and C,D in X**2** setting;

e) calculate Sij parameters at target point (X**1**.t,X**2**.t) as an average of a second set of linear interpolations one between the points A and B and one between the points C and D.

6. An impedance synthesis (tuning) method of the load-pull tuner of claim **2** comprising:

a) define a frequency F and an associated tuner calibration file;

b) define a tuning target, in form of a reflection factor Γ=|Γ|*exp(jΦ), and a maximum number of iterations NMAX;

c) select a highest penetration setting SPT of the resistive septum;

d) download s-parameters Sij(SPT,X**1**,X**2**) from the tuner calibration file for the selected septum penetration setting SPT;

e) search for a maximum reflection factor |S**11**(SPT,X**1**, X**2**)| in the downloaded s-parameter Sij(SPT,X**1**,X**2**) data;

f) if the maximum reflection factor |S**11**(SPT,X**1**,X**2**)| is smaller than the target reflection factor |Γ|, reduce the penetration setting SPT of the septum and go to step (d);

g) search for a calibration point S**11**(SPT,X**1**o,X**2**o), for which an error function EF, defined as the square of the absolute vector difference between Γ and the reflection factor S**11**(SPT,X**1**o,X**2**o) at the setting SPT of the septum and the tuning probe positions X**1**o and X**2**o ($EF=|S11(SPT,X1o,X2o)-\Gamma|^2$) is minimum;

h) set N=1 and search interpolated s-parameter data S**11**(SPT,X**1**,X**2**) in the area (X**1**,X**2**) surrounding the tuner setting (SPT,X**1**o,X**2**o) for a final setting (SPT, X**1**.final,X**2**.final) as follows:

h1) from the tuner setting (SPT,X**1**o,X**2**o) in a X**1** iteration loop:

set N=N+1 and change the probe setting X**1**o by a small amount δX**1** to X**1**o+δX**1**, whereby δX**1** is proportional to the change of the Error Function EF=|S**11**(SPT,X**1**o+δX**1**,X**2**o)−Γ|^2), until the error function EF reaches a minimum, and define X**1**o'=X**1**o+δX**1**;

h2) from a new tuner setting (SPT,X**1**o',X**2**o) in a X**2** iteration loop:

set N=N+1 and change the probe setting X**2**o by a small amount δX**2** to X**2**o+δX**2**, with δX**2** proportional to the change of the Error Function EF=|S**11**(SPT,X**1**o',X**2**o+δX**2**)−Γ|^2, until the error function EF reaches a minimum, and define a new probe position X**2**o'=X**2**o+δX**2**;

h3) set probe positions X**1**o=X**1**o', X**2**o=X**2**o' and repeat steps h1) and h2) until there is no further reduction of the error function EF, or if the number N of iterations exceeds the maximum number of iterations NMAX;

h4) define probe positions X**1**.final=X**1**o' and X**2**.final=X**2**o';

i) move the tuning probe P#**1** to position X**1**.final and the tuning probe P#**2** to position X**2**.final.

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