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Tsironis

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(54) **LOAD PULL SYSTEM USING WAVEGUIDE TUNER**

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G01R 27/32 (2006.01)
G01R 31/28 (2006.01)
G01R 35/00 (2006.01)

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

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

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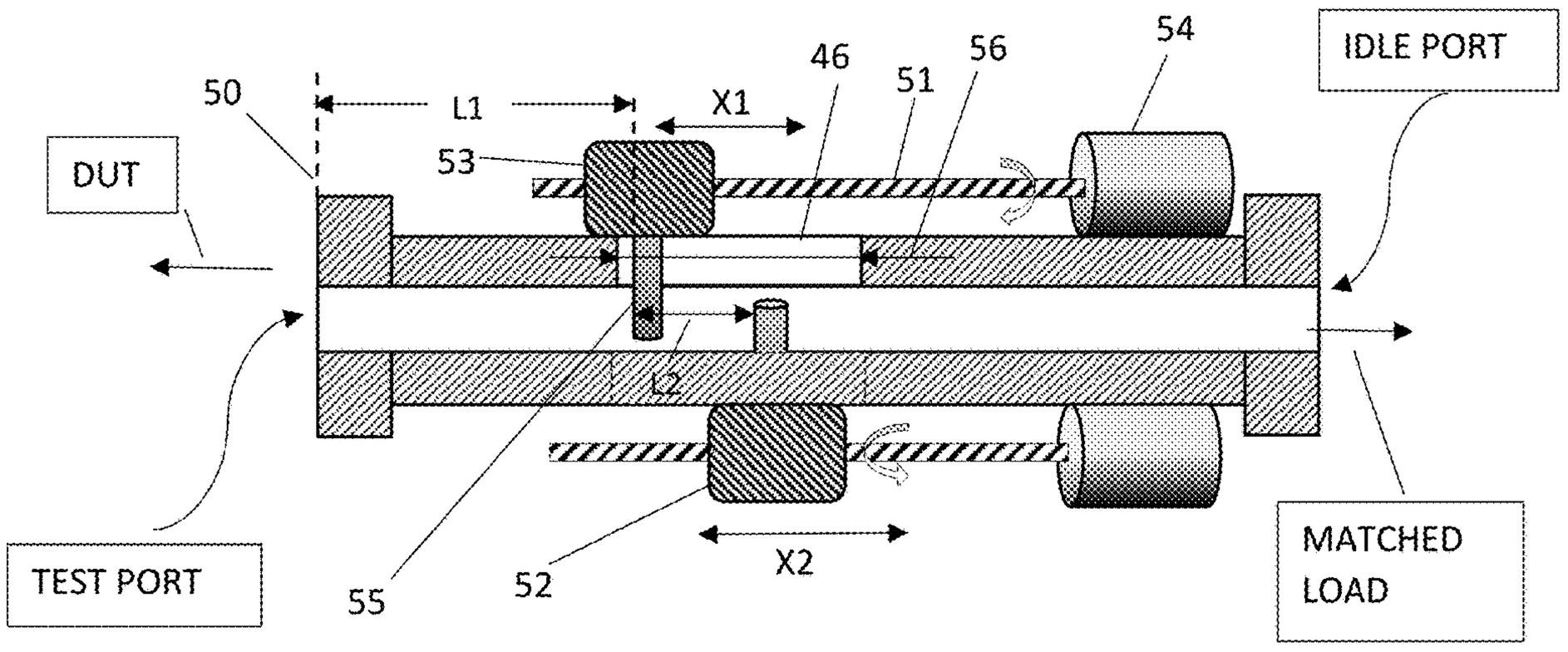
Primary Examiner — Akm Zakaria

(57) **ABSTRACT**

A load-pull measurement system uses a PC controller, interface, calibration method and at least one new two-probe, waveguide slide screw impedance tuner; the tuner probes share the same waveguide section; they are inserted diametrically at fixed depth into facing each other slots on opposite broad walls of the waveguide. 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.

7 Claims, 12 Drawing Sheets



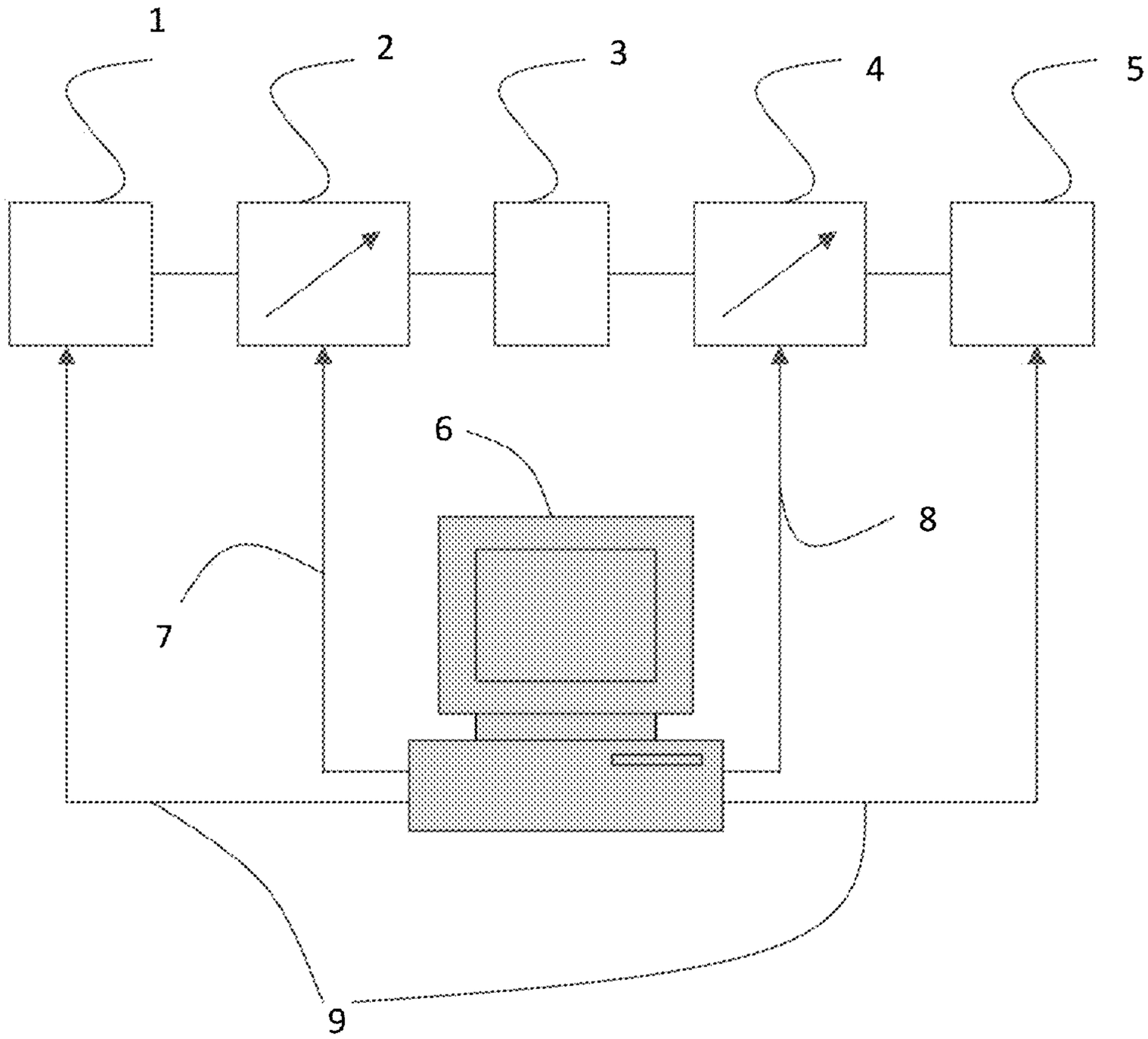


FIG. 1: Prior art

FIG. 2A: Prior art

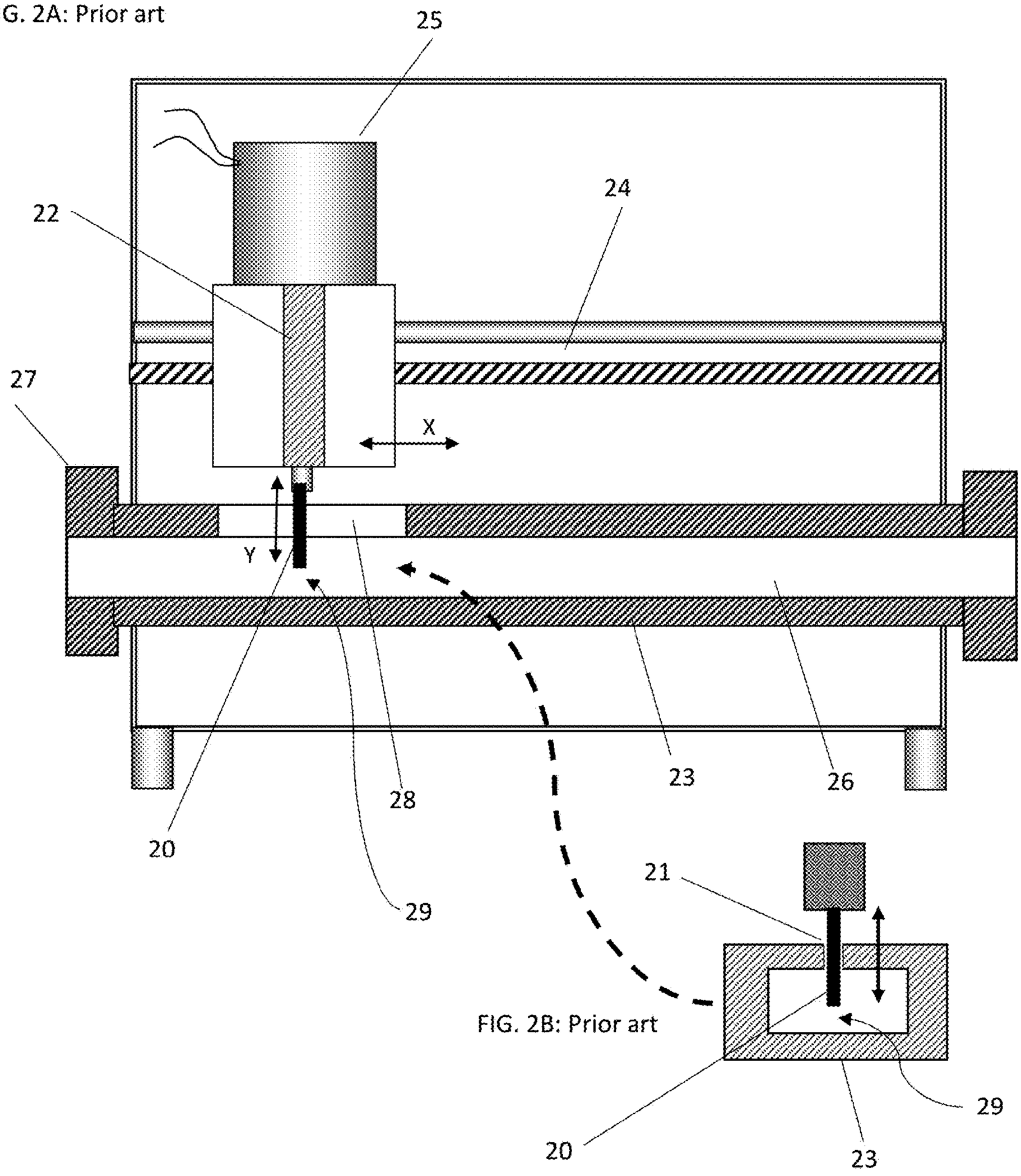


FIG. 2B: Prior art

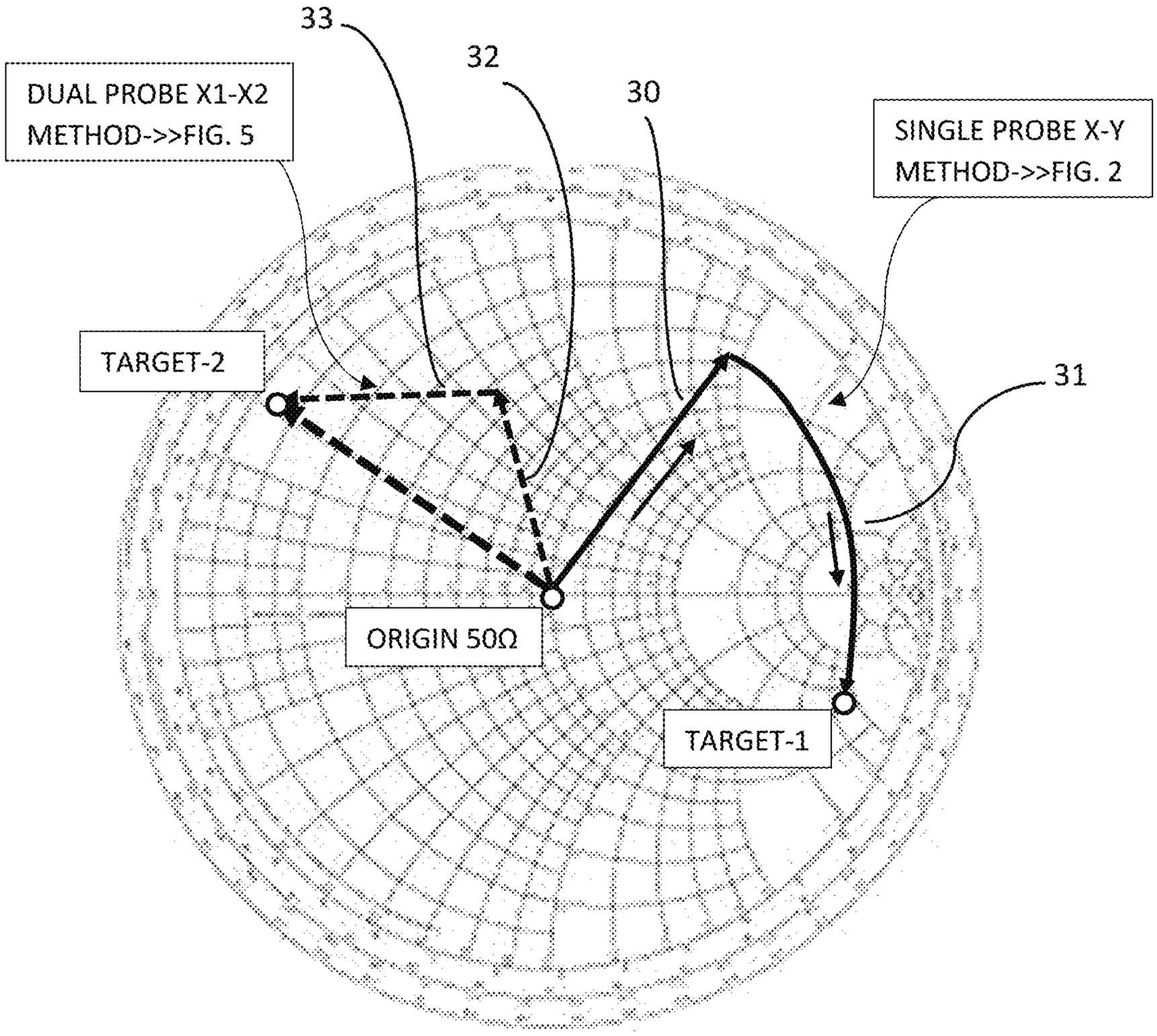

33
32
30
DUAL PROBE X1-X2
METHOD->>FIG. 5
SINGLE PROBE X-Y
METHOD->>FIG. 2
TARGET-2
31
ORIGIN 50Ω
TARGET-1

FIG. 3

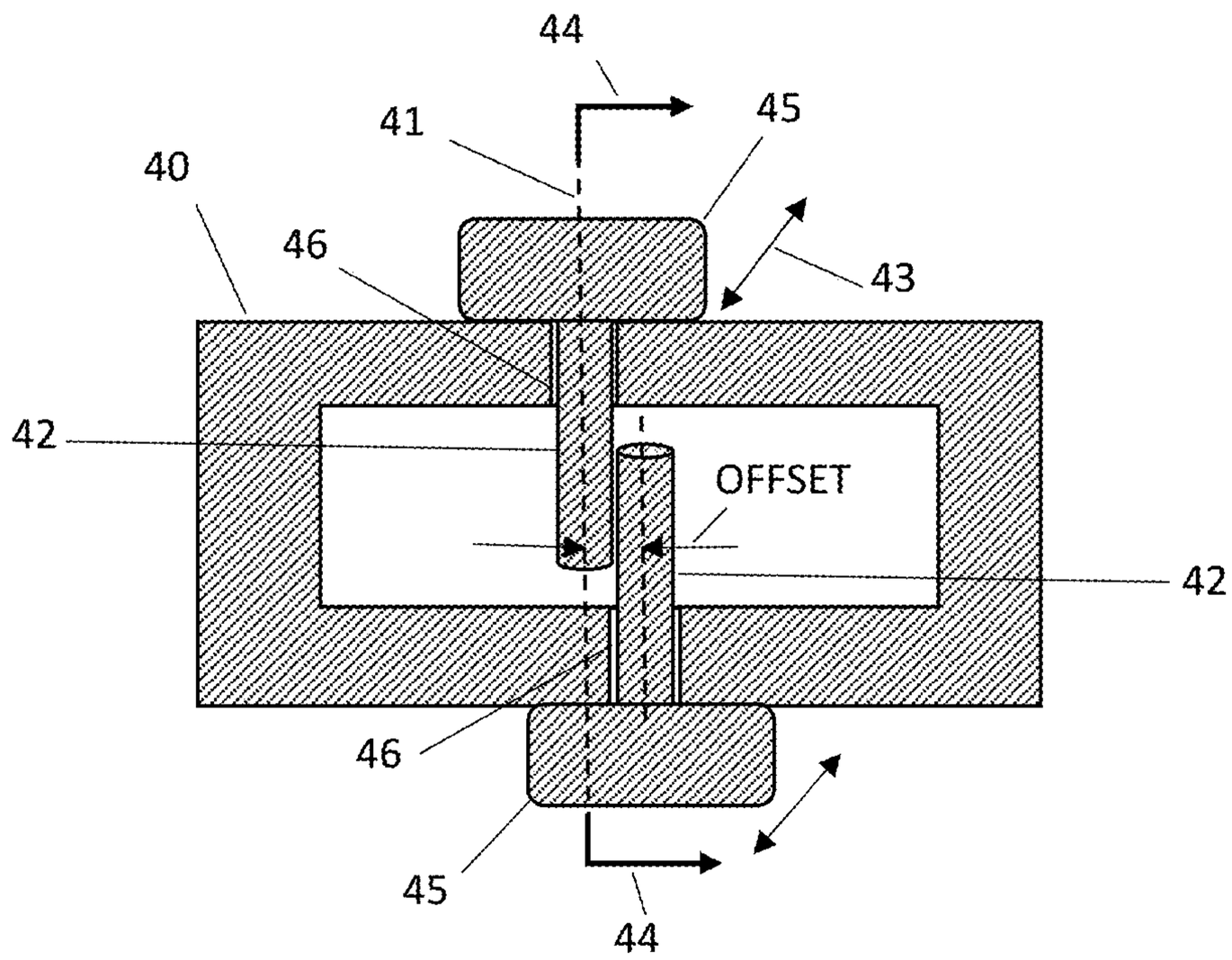


FIG. 4

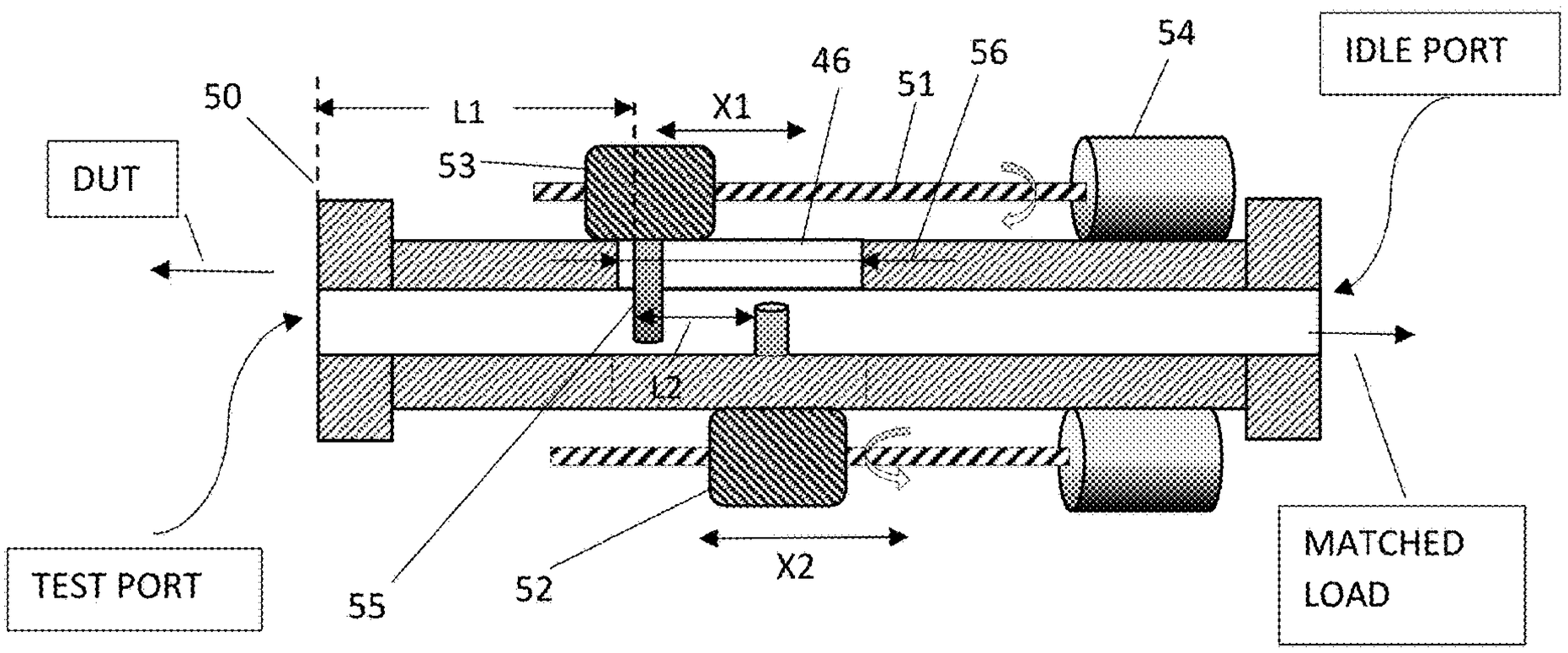

50
L1
X1
46
51
56
54
IDLE PORT
53
DUT
L2
TEST PORT
55
52
X2
MATCHED
LOAD

FIG. 5

FIG. 6A

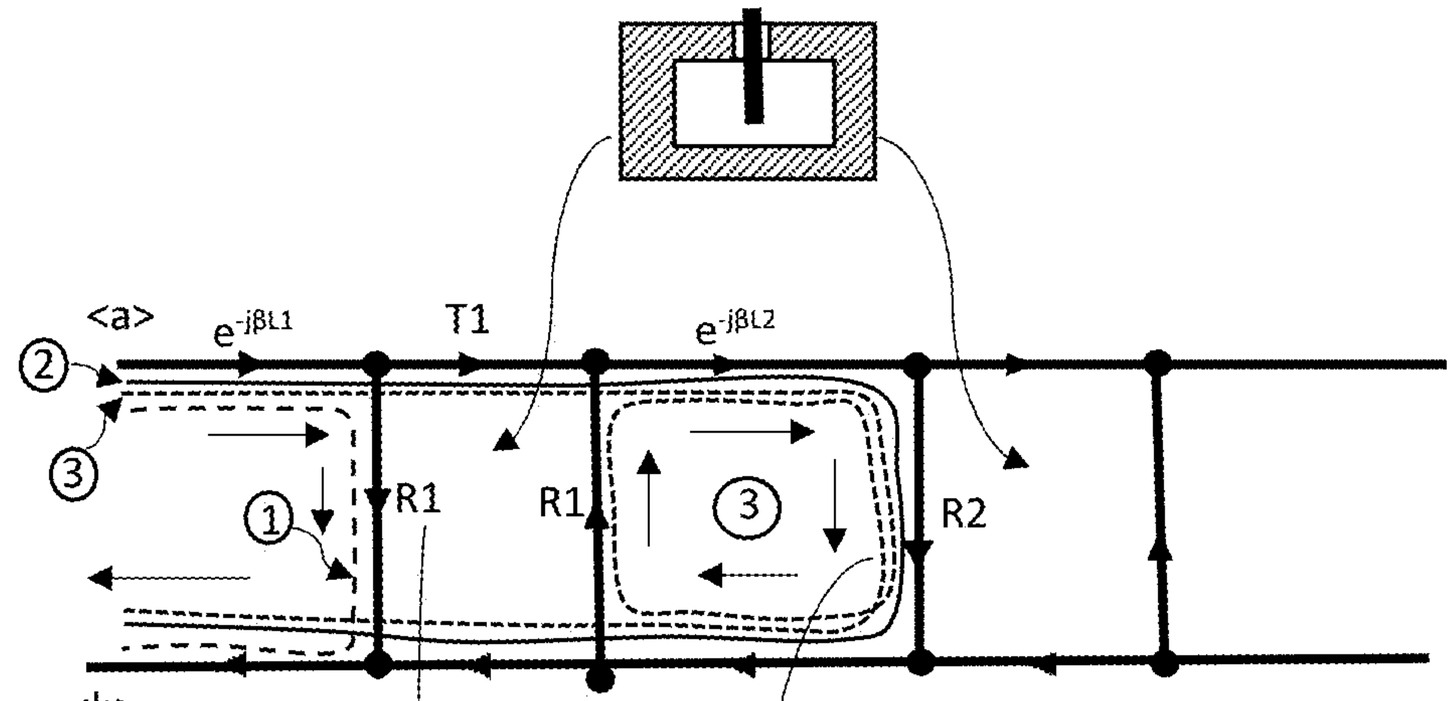
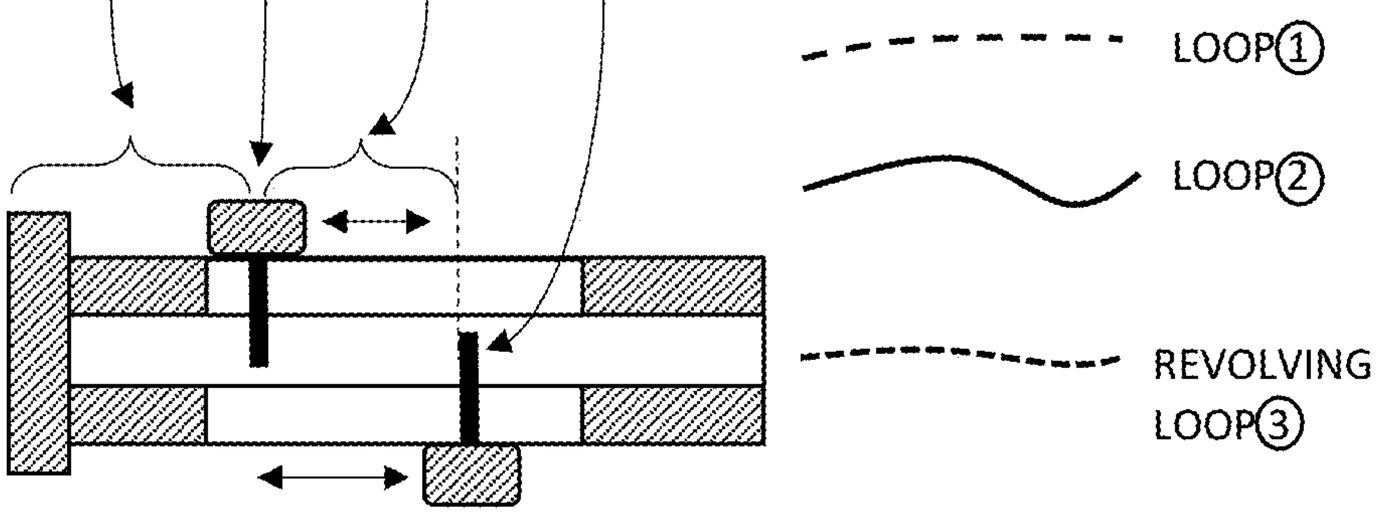


FIG. 6B

FIG. 6C



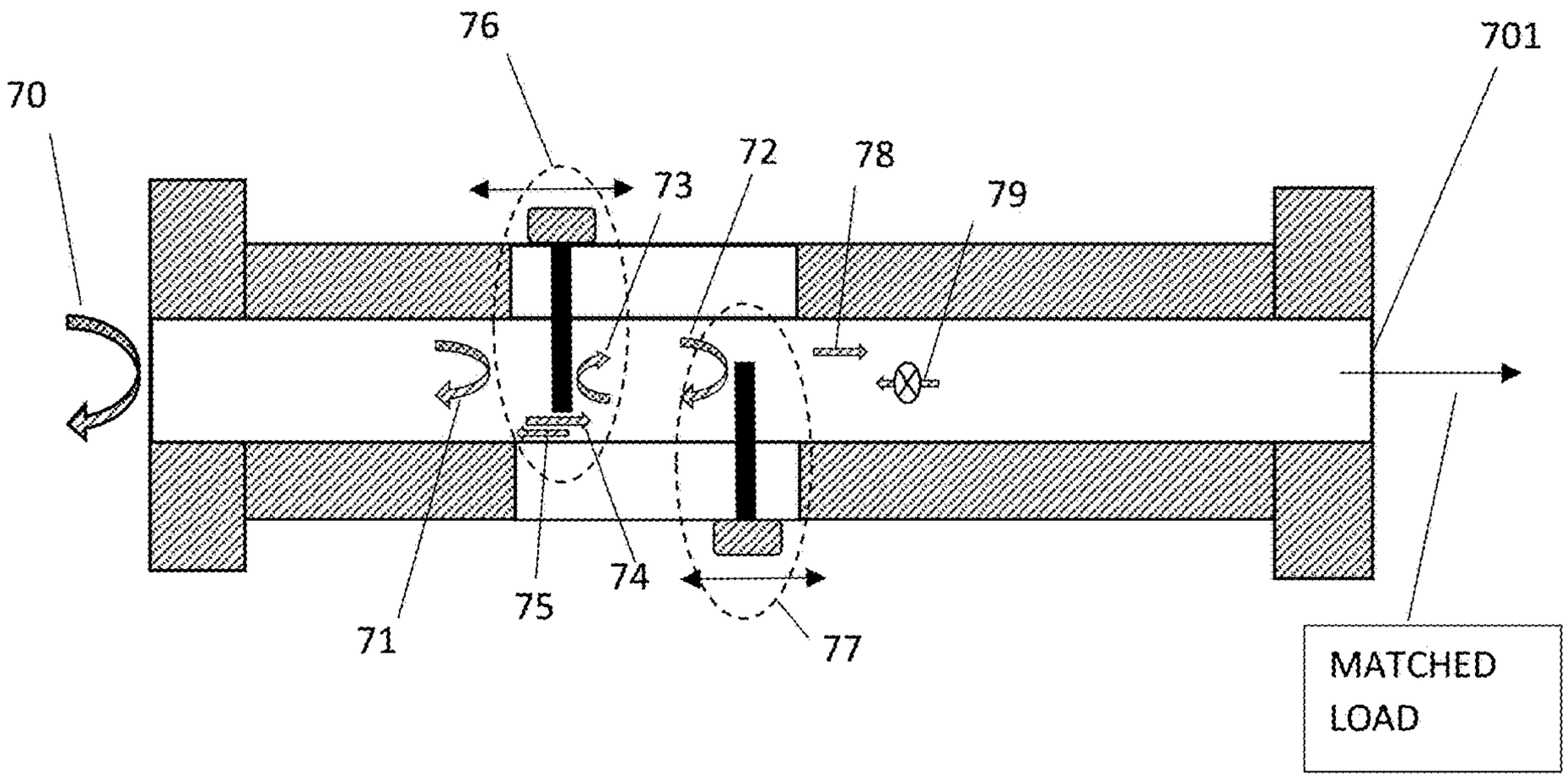


FIG. 7

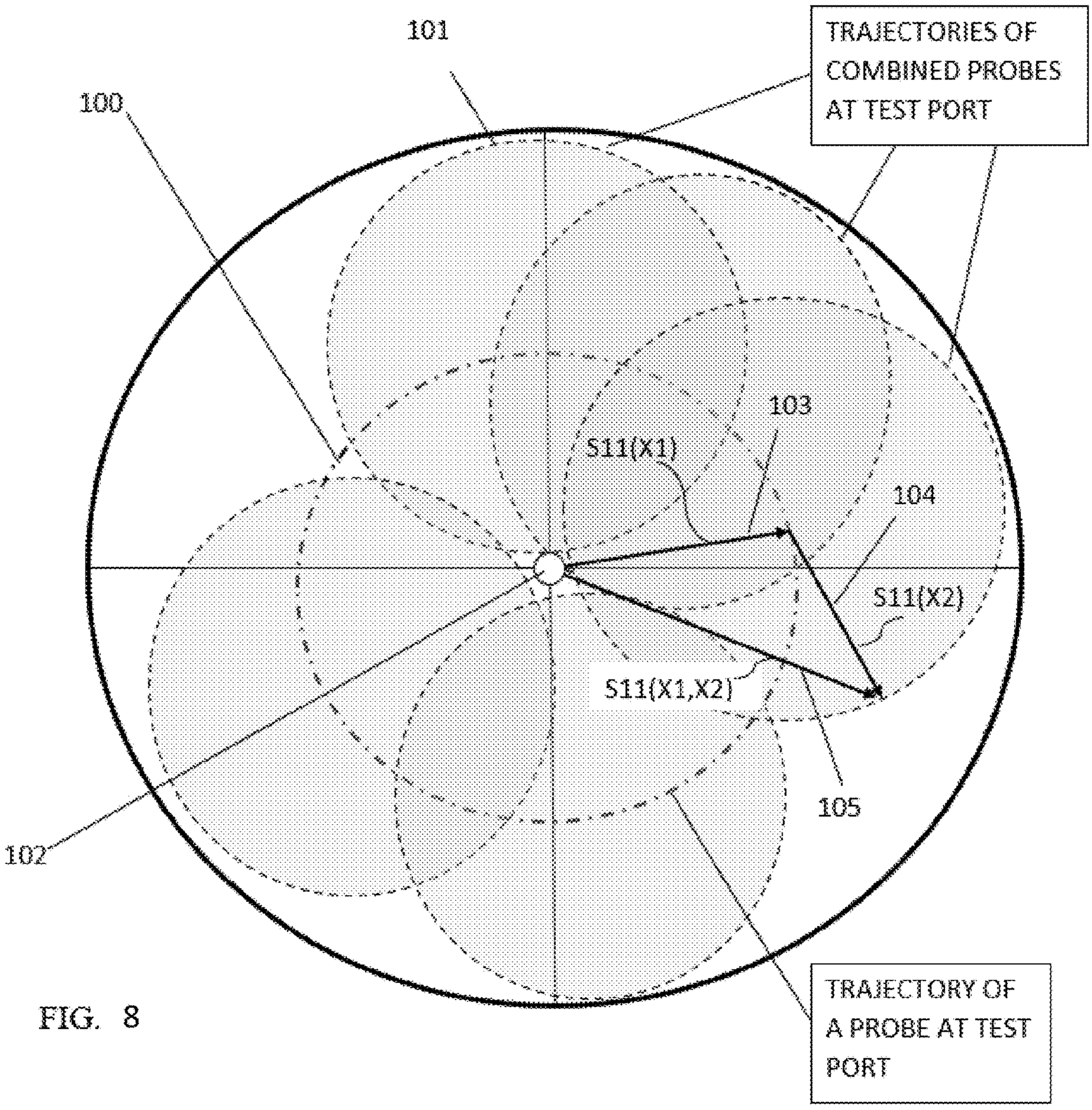

101
TRAJECTORIES OF COMBINED PROBES AT TEST PORT
100
103
S11(X1)
104
S11(X2)
S11(X1,X2)
105
102
TRAJECTORY OF A PROBE AT TEST PORT

FIG. 8

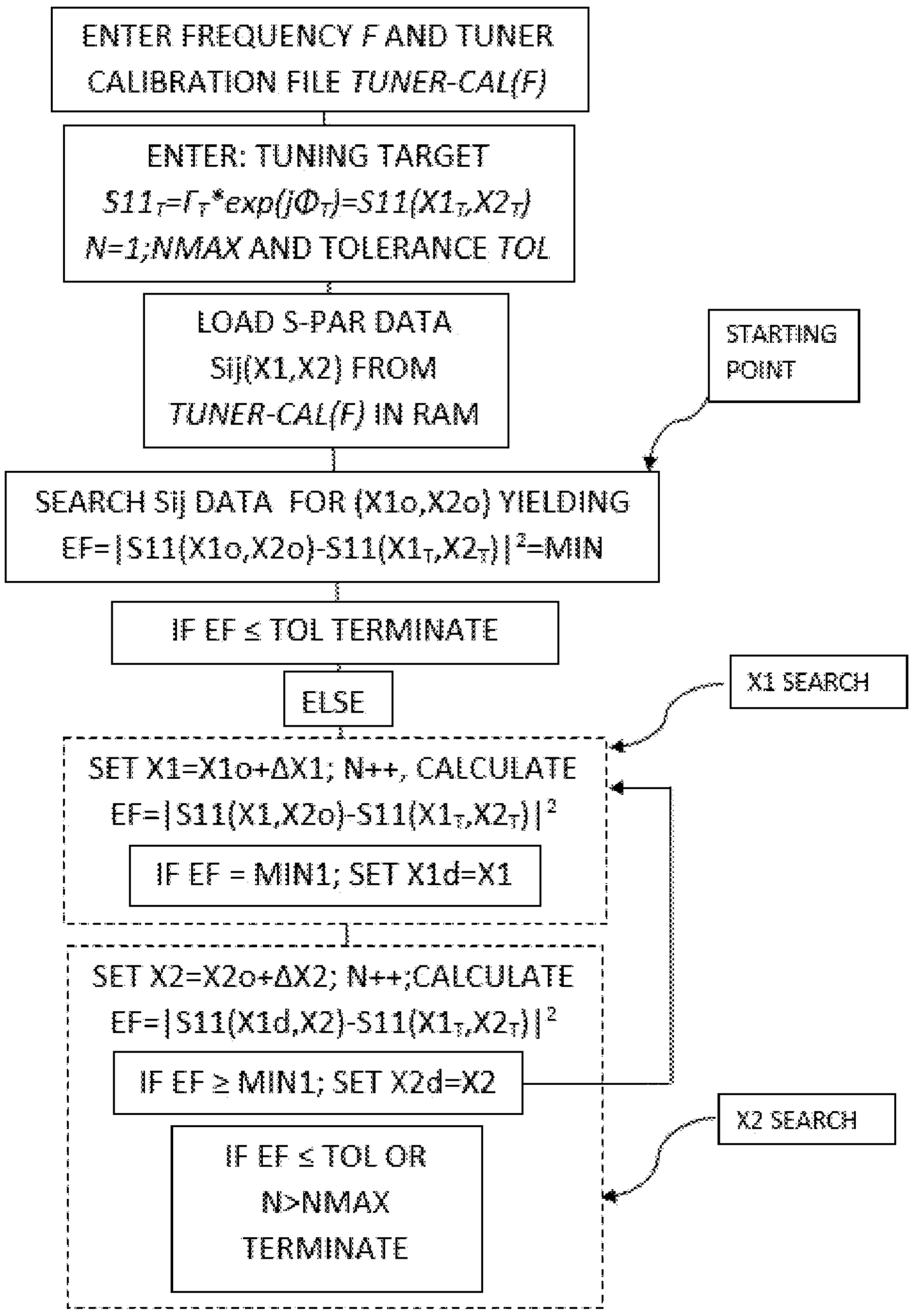

ENTER FREQUENCY F AND TUNER CALIBRATION FILE TUNER-CAL(F)
ENTER: TUNING TARGET
S11T=ΓT*exp(jΦT)=S11(X1T,X2T)
N=1;NMAX AND TOLERANCE TOL
LOAD S-PAR DATA Sij(X1,X2) FROM TUNER-CAL(F) IN RAM
STARTING POINT
SEARCH Sij DATA FOR (X1o,X2o) YIELDING
EF=|S11(X1o,X2o)-S11(X1T,X2T)|2=MIN
IF EF ≤ TOL TERMINATE
ELSE
X1 SEARCH
SET X1=X1o+ΔX1; N++, CALCULATE
EF=|S11(X1,X2o)-S11(X1T,X2T)|2
IF EF = MIN1; SET X1d=X1
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. 9

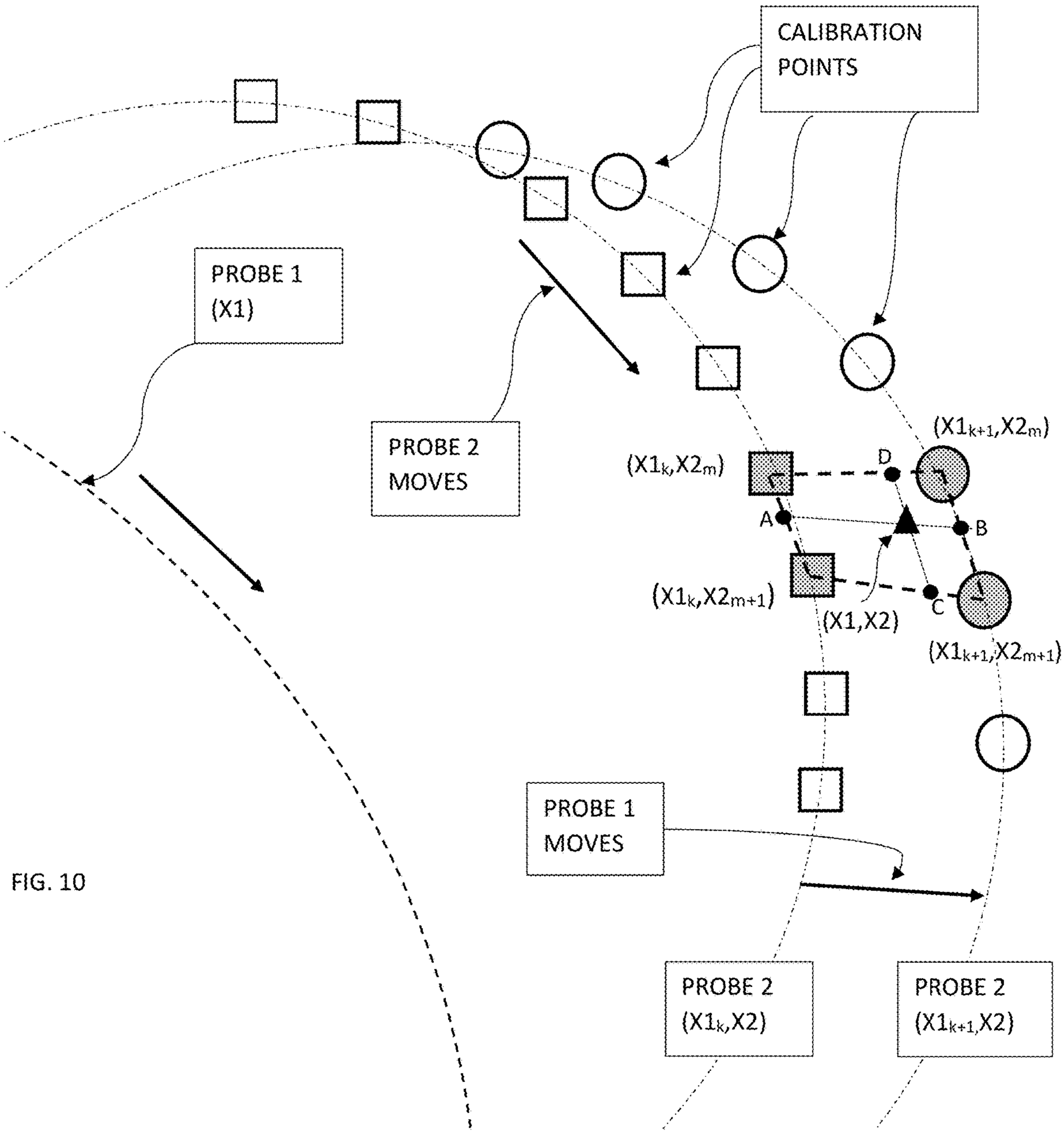

CALIBRATION POINTS
PROBE 1 (X1)
PROBE 2 MOVES
$(X1_{k+1},X2_m)$
$(X1_k,X2_m)$
D
A
B
$(X1_k,X2_{m+1})$
C
(X1,X2)
$(X1_{k+1},X2_{m+1})$
PROBE 1 MOVES
PROBE 2 $(X1_k,X2)$
PROBE 2 $(X1_{k+1},X2)$

FIG. 10

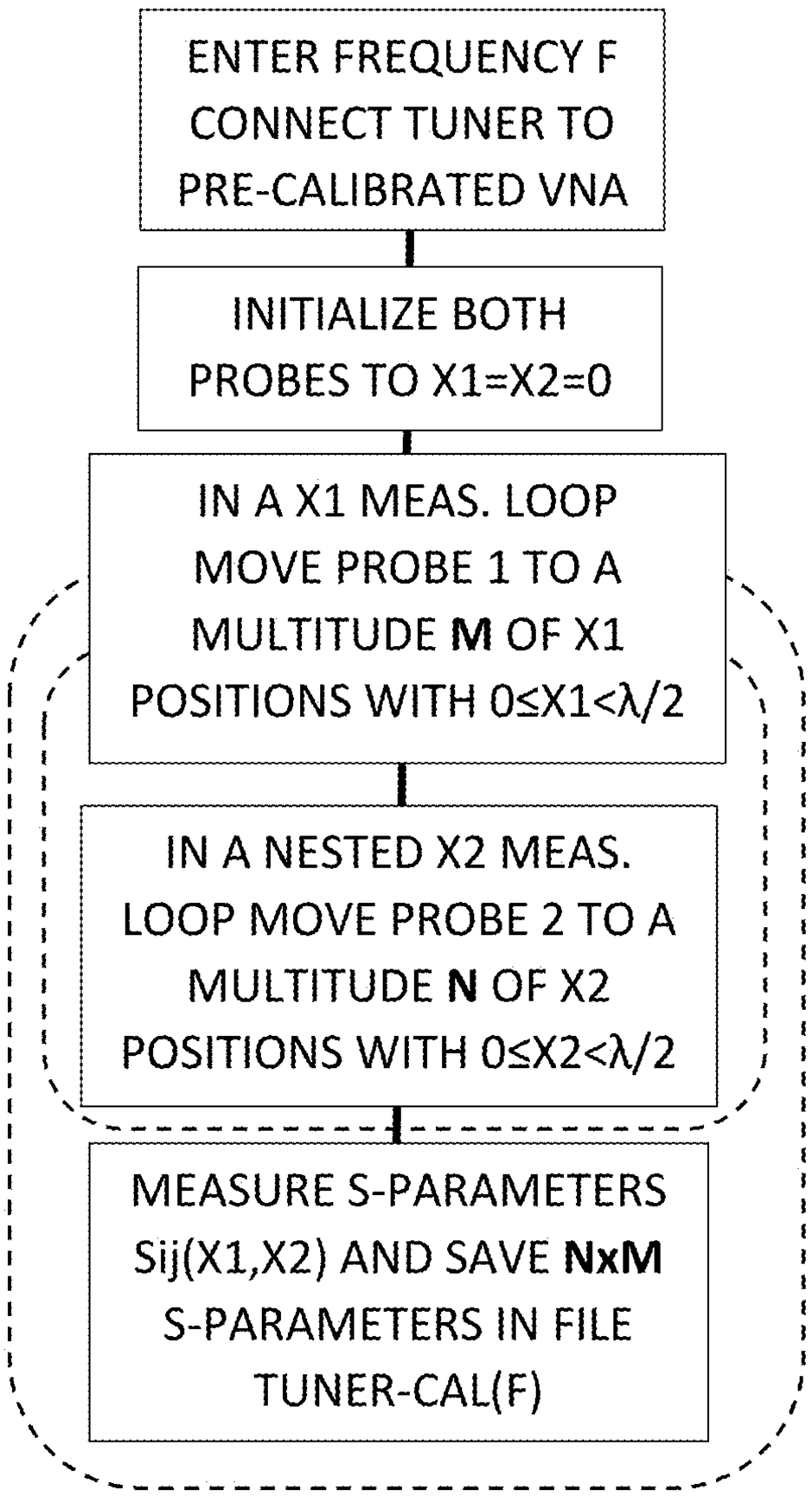

ENTER FREQUENCY F
CONNECT TUNER TO PRE-CALIBRATED VNA
INITIALIZE BOTH PROBES TO X1=X2=0
IN A X1 MEAS. LOOP MOVE PROBE 1 TO A MULTITUDE **M** OF X1 POSITIONS WITH 0≤X1<λ/2
IN A NESTED X2 MEAS. LOOP MOVE PROBE 2 TO A MULTITUDE **N** OF X2 POSITIONS WITH 0≤X2<λ/2
MEASURE S-PARAMETERS Sij(X1,X2) AND SAVE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

FIG. 11

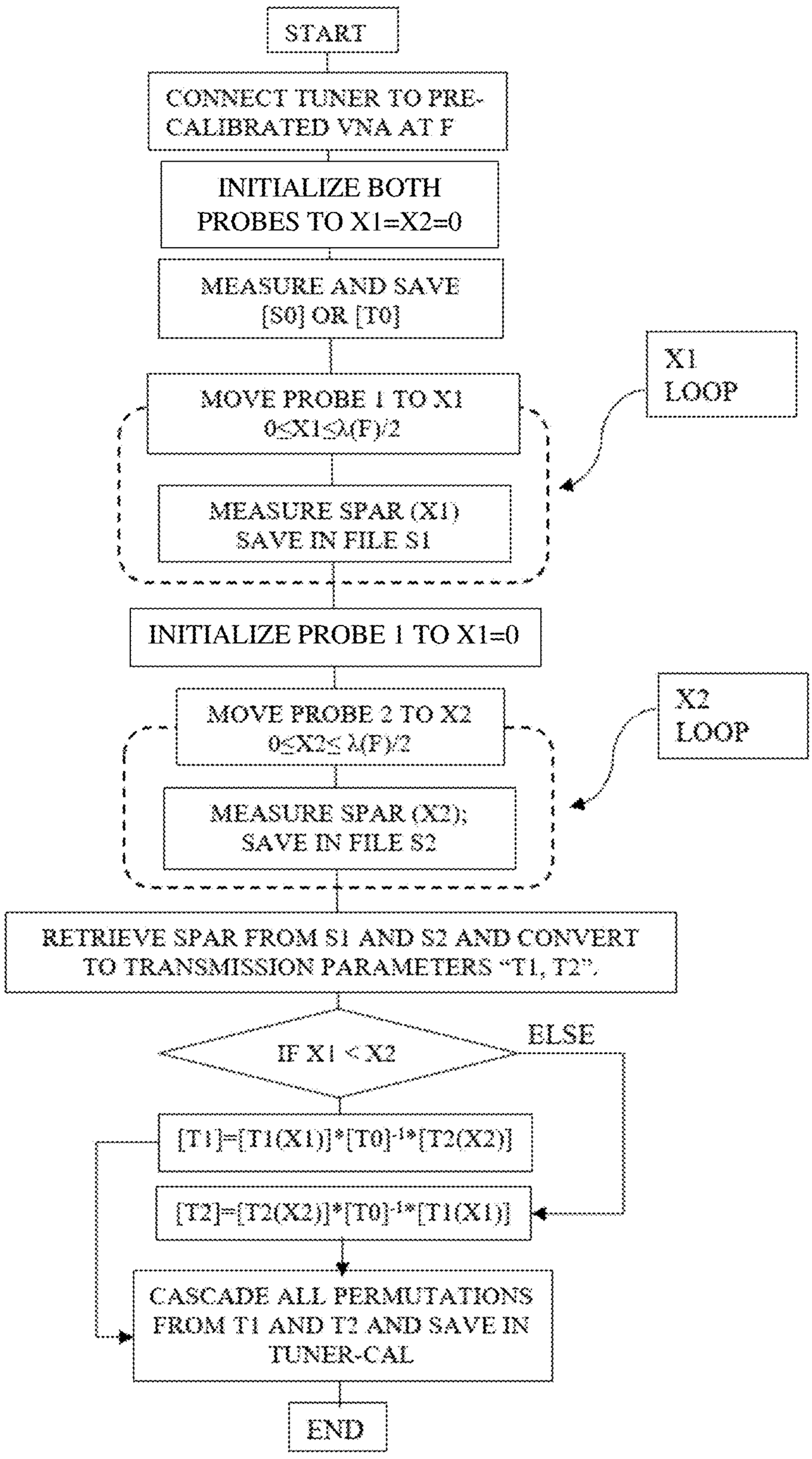

START
CONNECT TUNER TO PRE-CALIBRATED VNA AT F
INITIALIZE BOTH PROBES TO X1=X2=0
MEASURE AND SAVE [S0] OR [T0]
X1 LOOP
MOVE PROBE 1 TO X1 0≤X1≤λ(F)/2
MEASURE SPAR (X1) SAVE IN FILE S1
INITIALIZE PROBE 1 TO X1=0
X2 LOOP
MOVE PROBE 2 TO X2 0≤X2≤ λ(F)/2
MEASURE SPAR (X2); SAVE IN FILE S2
RETRIEVE SPAR FROM S1 AND S2 AND CONVERT TO TRANSMISSION PARAMETERS "T1, T2".
IF X1 < X2
ELSE
[T1]=[T1(X1)]*[T0]-1*[T2(X2)]
[T2]=[T2(X2)]*[T0]-1*[T1(X1)]
CASCADE ALL PERMUTATIONS FROM T1 AND T2 AND SAVE IN TUNER-CAL
END

FIG. 12

LOAD PULL SYSTEM USING WAVEGUIDE TUNER

PRIORITY CLAIM

Not Applicable

CROSS-REFERENCE TO RELATED ARTICLES

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8. "Regula falsi" [online], Wikipedia [retrieved on Aug. 26, 2021]. Retrieved from Internet <URL: https://en.wikipedia.org/wiki/Regula_falsi>.
9. "Lecture 20: Transmission (ABCD) Matrix" [online], EE 481/581—Microwave Engineering, Course Syllabus [retrieved on Jul. 13, 2015] Retrieved from Internet <URL: https://whites.sdsmt.edu/classes/ee481/notes/481Lecture20>.

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 impedance (load-pull) tuners and other microwave 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 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 the 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 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 rods) **20**, FIG. **2**, penetrate into the waveguide **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** 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. 3) 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 to be able to create path **30** in FIG. **3** and tune. Neither relevant prior art ref. 3, 4 or 7 teach a compact waveguide tuner using alternatively swapping and crossing over tuning probes in a shared transmission line structure. 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 load pull measurement system using a new type slide screw tuner and associated control software. The tuner configuration, different from prior art, uses horizontal-only high-speed movement techniques of the tuning probes and also a preferred fast, custom impedance synthesis (tuning) method, once the tuner is properly calibrated.

The impedance tuner itself, of which a conceptual cross section is shown in FIG. **4**, uses a low loss waveguide transmission line **40** and two diametrical tuning probes **42**. The tuning probes **42** are, typically, conductive rods and are mounted on mobile carriages **45**. The carriages are placed facing each-other across the waveguide and slide **43** seamlessly and precisely along the waveguide top and bottom walls. They hold the tuning probes (conductive rods) **42** and keep them inserted at a fixed depth in vertical slots **46**, which are parallel to the axis of the waveguide i.e., there is no need for any vertical probe control. In order to allow the tuning rods to cross over without mechanical conflict, the slots are

slightly offset of the center line of the waveguide, by at least one diameter (thickness) of a tuning rod. A medium size reflection (S11≈0.5-0.7) is created by either tuning rod leading to a different tuning mechanism as shown in FIG. **3** (traces **32**, **33**). Both tuning mechanisms shown in FIG. **3** yield the same result: starting from the matched load (50Ω) they allow tuning to targets 1 or 2. The result is the same, only the control mechanisms differ.

The carriages **45**, **52**, **53** are controlled using high-speed electric stepper motors **54** and ACME rods **51** or actuators (see ref. 6) 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 |Γ|≈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 two possible trajectories of impedance synthesis (tuning) to reach a target impedance starting from the origin of 50Ω. Reaching target-1 uses the prior art single-probe technique with horizontal and vertical control; reaching target-2 uses the new two-probe technique with horizontal only and without vertical control.

FIG. **4** depicts a cross-section through a waveguide 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.

FIGS. **6**A through **6**C depict the signal flow graph (SFG) of the two-probe impedance tuner: FIG. **6**A depicts the reflection area of a tuning probe; FIG. **6**B depicts the overall signal flow graph; FIG. **6**C identifies the signal transmission and nodes of the tuner depicted in the signal flow graph.

FIG. **7** depicts signal flow and multiple reflections created by the two probes 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.

FIG. **9** depicts the flowchart of the impedance synthesis (tuning) process.

FIG. **10** depicts the tuning vector composition and interpolation strategy of the two-probe tuner with fixed probe insertion depth and shared waveguide.

FIG. **11** depicts the flowchart of the calibration algorithm of the shared-waveguide 2-probe fixed-penetration tuner.

FIG. **12** depicts the flowchart of the fast de-embedding calibration algorithm of the shared-waveguide 2-probe fixed-penetration tuner.

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/bottom walls, two narrow sidewalls and two slots **46** cut into the broad walls, one on the top wall and one on the bottom wall. The slots run parallel to the waveguide longitudinal axis and 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 preferred for economy of space, because it uses slots of a total length of one half of a wavelength **56** plus the thickness of one tuning rod. An alternative configuration, where the tuning rods would not cross over, would, in principle also work, but the slot or the sum of the slots (and the tuner) would have to be twice as long. The horizontal control of the carriages **52** and **53** can, instead of motor and ACME screws, can also be accomplished using linear electric actuators (see ref. 6); the actuators have a motorized body, and their rotor axis is replaced by the extended horizontal ACME screw **51**.

FIG. **5** shows a front view of the waveguide tuner as seen in the cross section **41**, **44** of FIG. **4**: the slots **46** can be seen, to allow the tuning probes (rods or blocks) to traverse contactless **21**, and their effective length **56** is seen as well; the mobile carriages **52** and **53** are controlled by the ACME screw **51** along the waveguide via the stepper motors **54**; the reference position of carriage **53** is X**1** and of carriage **52** is X**2** relative to a common arbitrary zero position. The zero position must be common, because the calibration routine requires knowledge of the position of each probe relative to the test port. The electric distance of the first tuning probe **55** from the test port **50** is L**1** and the electric distance between the two tuning probes is L**2**; the lower slot **46** is hidden in FIG. **5** as it is evident from the view through the cross section **44** in FIG. **4**.

The signal propagation trajectories are shown in FIG. **7**: the total reflection factor **70** is a function of the combined positions X**1** and X**2** of the two probes: S**11**(X**1**,X**2**) and is the vector-sum of the reflection factors **71** and **75** of both probes S**11**(X**1**) and S**11**(X**2**): S**11**(X**1**,X**2**)=S**11**(X**1**)+S**11**(X**2**), (eq. 6) all referenced at the test port **70**. The tuning probe **76**, in this configuration closest to the test port, generates the primary reflection **71**. Since this reflection is selected not to be total, there is a signal portion **74** traversing towards the secondary tuning 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 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 terms this appears like a turbulence. This back and forth bouncing of signal is well described using signal flow graphs (see ref. 5). Instead, since the tuner is terminated **701** with a matched load any escaping signal **78** is not reflected back **79** and therefore ignored.

FIG. **6**B shows the signal flow graph describing the tuner, which is also shown schematically in FIG. **6**C: Each pair of nodes represent a port and each branch the complex signal flow factor S**11**&S**22** or S**21**&S**12** between the ports; each tuning probe (FIG. **6**A) 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** generates R**1** and T**1**, probe **2** generates

R2 and T2. The injected signal <a> returns as <b> after following several loops: between each probe there is a delay exp(−jβL); loop **1** represents the primary reflection, loop **2** the secondary reflection and loop **3** the multiple reflections; it must be remarked that loop **3** is revolving (repeating) adding each time a decreasing amount to the total reflection **70**; loop **3** resumes in an infinite, but rapidly converging, series of reflected signal power vectors generating the overall reflection vector **70**. The transmission factors T**1** and T**2** represent the portion of signal traversing the tuning probe, whereas the reflection factors R**1** and R**2** represent the reflected portion. Transmission lines are described by simple phase delays $\beta=2\pi/\lambda$. Assuming the probes represent capacitors C**1** and C**2** 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 $T2=2/(2+j\omega C2Zo)$. The section after probe **2** is matched to 50Ω, therefore signal is not returning and the associated R**2** and T**2** are 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: $S11=<b>/<a>\{e^{-j\beta L1}-R1-e^{-j\beta(L1+L2)}\cdot R2\cdot T1^2-e^{-j\beta(L1+2L2)}\cdot T1^2 R2^2\cdot R1+\}$ . . . ; the series of loops is truncated, since the third loop (LOOP **3**) is repeated n times with n=1,2,3,4 . . . towards infinite, but its 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 $T1^{4n}$, $R1^{2n}$, $R2^{4n}$ etc. are smaller than 1 and rapidly vanishing, 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).

The tuner calibration process at a given frequency F is possible using a traditional method (FIG. **11**) consisting in measuring, on a pre-calibrated vector network analyzer (VNA) s-parameters between the test and idle ports (FIG. **5**) for all N*M permutations of 1,2,3 . . . N times X**1** and 1,2,3 . . . M times X**2** tuning probe positions, with typical 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 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 fast de-embedding calibration method allows a must faster operation as follows: measure first the s-parameters of the slabline with both probes initialized (X**1**=X**2**=0) and save in a zero matrix [S**0**]; then move probe **1** to a multitude of N 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**; then initialize probe **1** to X**1**=0, move probe **2** to a multitude M positions X**2**, measure s-parameters Sij(X**2**) and save in a file S**2**. Subsequently the data in files S**1** and S**2** 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 $[S0]^{-1}$ and re-saved in file S**2**; else, if X**1**>X**2**, then Sij(X**1**) is de-embedded, i.e., cascaded with $[S0]^{-1}$ and re-saved in file S**1**; subsequently all M*N permutations of the s-parameters in updated files S**1** and S**2** 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; presumably all s-parameter matrix cascading is executed after converting s-parameters to ABCD or transfer (T-parameters), see ref. 9, and back to s-parameters; the result of this operation lasts much less than before: a total of M+N points are measured and data are processed very fast in memory. The total time (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 X**1** and X**2** positions (steps), in which case we have 1 million or more tunable impedances). The interpolation routine allows accurate determination of the s-parameters Sij(X**1**,X**2**) of the tuner for any arbitrary probe settings (X**1**,X**2**) of the tuning probes, 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 X**1** or the X**2** direction or trace of probe movement (FIG. **10**); herein the calibrated probe positions are selected to be successive: $X1_k\leq X1<X1_{k+1}$ (on the X**1** trace) and $X2_m\leq X2<X2_{m+1}$ (on the X**2** trace), in order to create a polygon between the above calibrated points, that includes the tunable point with target coordinates (X**1**,X**2**); 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:

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

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

$$Sij(C)=Sij(X1_k,X2_m1)+(X1-X1_k)/(X1_k1-X1_k)\cdot(Sij(X1_{k+1},X2_{m+1})-Sij(X1_k,X2_{m+1})); \quad [eq.3]$$

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

In step 2 then, a new linear interpolation generates Sij(X**1**, X**2**) 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(X**1**,X**2**) data are saved in a calibration file TUNER-CAL (F) at a frequency F, 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. **9**): 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 loads the data of the tuner calibration file in random access (fast) RAM memory. The actual tuning process then, either automatically or manually triggered, imports one or more target reflection factors Γ or impedances Z. The search starts by comparing the calibrated reflection factors S**11**(X**1**,X**2**) saved in the calibration data with each imported r and determines a set of starting values (X**1***o*,X**2***o*) 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 X**1***o*,X**2***o* values are saved, and

the search terminates with X1.final=X1*o* and X2.final=X2*o*. Else, starting with X1*o*,X2*o*, the process modifies X1 and X2 alternatively by small amounts δX1 and δX2, which are proportional (in a regula falsi kind of algorithm, see ref. 8) to the change of the error function EF, the new interpolated value S11(X1,X2) 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 or 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 such 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**).

FIG. **8** depicts schematically the overall reflection factor synthesis mechanism: each probe creates at its own reference plane **71** or **72** (FIG. **7**) concentric reflection factor circles represented at test port reference plane as trace **100** on the Smith chart (FIG. **8**). The total reflection factor trace **101** is created by a planetary epicycloid superposition of the two reflection factor vectors around the center **102** (one circle rotates around a point at the periphery of the other). When the probes cross over the circles swap. The total reflection factor vector **105** is created by the vector sum of vector **103** (from the first probe) and the vector **104** (from the second vector) as described in equation 6.

FIG. **12** depicts the flowchart of the fast de-embedding calibration algorithm of the shared-waveguide 2-probe fixed-penetration tuner. The procedure executes as follows: After connecting to a pre-calibrated VNA, initialize both probes to X1=0, X2=0 and measure the initialization matrix [S0]=[S(0,0)]; then execute two loops, an {X1} loop and an {X2} loop, while keeping X2=0 and X1=0 correspondingly, measuring and saving s-parameters in files S1 and S2 correspondingly. In both cases X1 and X2 move between 0 and λ/2. After terminating, the data in files S1 and S2 are compared. When X1<X2 (i.e. if probe **1** is closer to the test port than probe **2**), then the data in S2 are de-embedded using $[S0]^{-1}$ and resaved, and if X1≥X2 it is the data in S1 that are de-embedded with $[S0]^{-1}$ and re-saved. Finally the matrix [S(X1,X2)] is created by concatenating (cascading) all updated S1 and S2 s-parameter permutations.

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. An automated load pull tuner comprising:

a slotted rectangular waveguide transmission line, having an input port and an output port,

two conductive broad walls and two conductive narrow sidewalls,

two remotely controlled mobile carriages C #**1** and C #**2** sliding along the waveguide transmission line,

wherein

each carriage controls a tuning probe inserted into longitudinal slots into the waveguide transmission line,

and wherein

the slots are placed diametral across the opposite broad walls of the waveguide transmission line,

and wherein

the mobile carriage C #**1** controls a tuning probe P #**1** and the mobile carriage C #**2** controls a tuning probe P #**2**.

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

wherein

the tuning probes are at least partially conductive rods, have a diameter D and fit contactless into the slots,

and wherein

the slots are positioned symmetrically offset of a center line along the waveguide transmission line by at least one half of the diameter D of the tuning probes, which are inserted diametral into the slots from the opposite broad walls and are kept at a fixed penetration into the slots during movement along the waveguide transmission line.

3. The automated load pull tuner of claim **2**,

wherein

the carriage C #**1** moves the tuning probe P #**1** to a position X**1** along the waveguide transmission line from the input port and the carriage C #**2** moves the tuning probe P #**2** to a position X**2** along the waveguide transmission line from the input port,

and wherein

the tuning probes P #**1** and P #**2** have a common initial position at a distance X**1**=X**2**=X**0** from the input port along the waveguide transmission line.

4. The automated load pull tuner of claim **2**,

wherein

the slots are at least one half of a wavelength (λ/2) long at a minimum frequency of operation (Fmin) of the automated load pull tuner.

5. A calibration method for the automated load pull tuner of claim **1** comprising the following steps:

a) connect the automated load pull tuner to a vector network analyzer, calibrated at a frequency F;

b) initialize both tuning probes by moving them to positions X**1**=X**2**=X**0** along the waveguide transmission line relative to the input port;

c) measure s-parameters of the automated load pull tuner and save in a zero matrix [S**0**];

d) in a movement-measurement loop:

move the tuning probe P #**1** to a multitude M>1 of positions X**1**,

whereby X**0**≤X**1**≤X**0**+λ(F)/2,

measure s-parameters Sij(X**1**), whereby {i,j}={1,2},

save (X**1**,Sij(X**1**)) in a data file S**1**;

e) move the probe P #**1** to the position X**1**=X**0**;

f) in a movement-measurement loop:

move the tuning probe P #**2** to a multitude N>1 of positions X**2**,

whereby X**0**≤X**2**≤X**0**+λ(F)/2,

measure s-parameters Sij(X2), whereby {i,j}={1,2}, save (X2,Sij(X2)) in a data file S2;

g) retrieve data (X1,Sij(X1)) from the data file S1 and (X2,Sij(X2)) from the data file S2;

h) in a scanning loop through the data (X1,Sij(X1)) for the multitude M of positions X1:

for each position X1 execute a nested scanning loop through the data (X2,Sij(X2)) for the multitude N of positions X2, and:

if (X1≤X2) then

h1) cascade (convert s-parameters to transfer parameters, multiply and convert back to s-parameters) the invers zero matrix $[S0]^{-1}$ with the s-parameters Sij(X2) of the data file S2 and replace in the data file S2;

else if (X1>X2) then

h2) cascade the invers s-parameter zero matrix $[S0]^{-1}$ with the s-parameters Sij(X1) of the data file S1 and replace in the data file S1;

i) retrieve the s-parameters Sij(X1) from the data file S1 and Sij(X2) from the data file S2, and:

if (X1≤X2) then

cascade the s-parameters of the file S1 with the s-parameters of the data file S2 to create Sij(X1, X2),

else if (X1>X2) then

cascade the s-parameters of the data file S2 with the s-parameters of the data file S1 to create Sij(X1, X2), and

j) save calibration data points in a format (X1, X2, Sij(X1,X2)) in a data file TUNER-CAL(F) for later use.

6. An interpolation method between calibrated data points for the automated load pull tuner as in claim **5** at a frequency F, comprising:

a) retrieve s-parameters Sij(X1,X2) of the calibrated data points from the tuner calibration data file TUNER-CAL (F);

b) define a target position with tuning probe coordinates (X1.*t*,X2.*t*);

c) identify, using a numeric search through the s-parameters retrieved in step (a), two pairs of successive calibration data points, one pair of successive X1 positions (X1.1 and X1.2) with X1.1≤X1.*t*≤X1.2, and one pair of successive X2 positions, (X2.1 and X2.2) with X2.1≤X2.*t*≤X2.2, which are closest to X1.*t* and X2.*t* correspondingly;

d) execute a first set of linear interpolations of s-parameters Sij including one interpolation of X1.*t* between the X1 successive positions (X1.1 and X1.2) and one interpolation of X2.*t* between the X2 successive positions (X2.1 and X2.2) yielding interpolated s-parameters Sij(A) and Sij(B);

e) execute a second set of linear interpolations of s-parameters Sij(X1,X2) including one interpolation of X1.*t* and X2.*t* between the positions X1.1 and X2.1 and one interpolation of X1.*t* and X2.*t* between the positions (X1.2 and X2.2) yielding interpolated s-parameters Sij(C) and Sij(D);

f) calculate Sij parameters at target point (X1.*t*,X2.*t*) as an average of a third set of linear interpolations of X1.*t* and X2.*t* between the s-parameters Sij(A) and Sij(B) and linear interpolations of X1.*t* and X2.*t* between the s-parameters Sij(C) and Sij(D).

7. An impedance synthesis (tuning) method for the automated two-probe waveguide load pull tuner of claim **6** comprising:

a) for a frequency F, define a tuning tolerance TOL and a tuner calibration data file and retrieve s-parameters Sij(X1,X2) from the calibration data file;

b) define a tuning target reflection factor $\Gamma=|\Gamma|*\exp(j\Phi)$ and a maximum number of iterations NMAX;

c) search in s-parameter Sij(X1,X2) for a calibration point Sij(X1*o*,X2*o*), for which an error function $EF=|S11(X1o,X2o)-\Gamma|^2$, defined as the square of the absolute vector difference between the reflection factor S11 (X1*o*,X2*o*) and the target Γ, is minimum;

d) if EF≤TOL, define X1.final=X1*o*, X2.final=X2*o* and move to step (f);

e) set N=1 and search interpolated s-parameter data S11(X1,X2) in the area (X1,X2) close to the calibrated point (X1*o*,X2*o*) for a final setting (X1.final,X2.final) as follows:

e1) from starting point (X1*o*,X2*o*), in a search loop of position X1 of the tuning probe P #1:

set N=N+1 and change X1*o* by a small amount δX1 to X1*o*+δX1, calculate the Error Function $EF=|S11(X1o+\delta X1,X2o)-\Gamma|^2$,

make δX1 proportional to the change of EF, increase N and iterate until EF reaches a minimum, and then set X1*o*'=X1*o*+δX1;

e2) from a new point (X1*o*',X2*o*), in a search loop of position X2 of the tuning probe P #2:

set N=N+1 and change X2*o* by a small amount δX2 to X2*o*+δX2, calculate the Error Function $EF=|S11(X1o',X2o+\delta X2)-\Gamma|^2$,

make δX2 proportional to the change of EF, increase N and iterate until EF reaches a minimum, and then set X2*o*'=X2*o*+δX2;

e3) set X1*o*=X1*o*', X2*o*=X2*o*' and repeat steps e1) and e2) until there is no further reduction of EF occurs or if N>NMAX;

e4) define X1.final=X1*o*', X2.final=X2*o*';

f) move the tuning probe P #1 to X1.final and tuning probe P #2 to X2.final.

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