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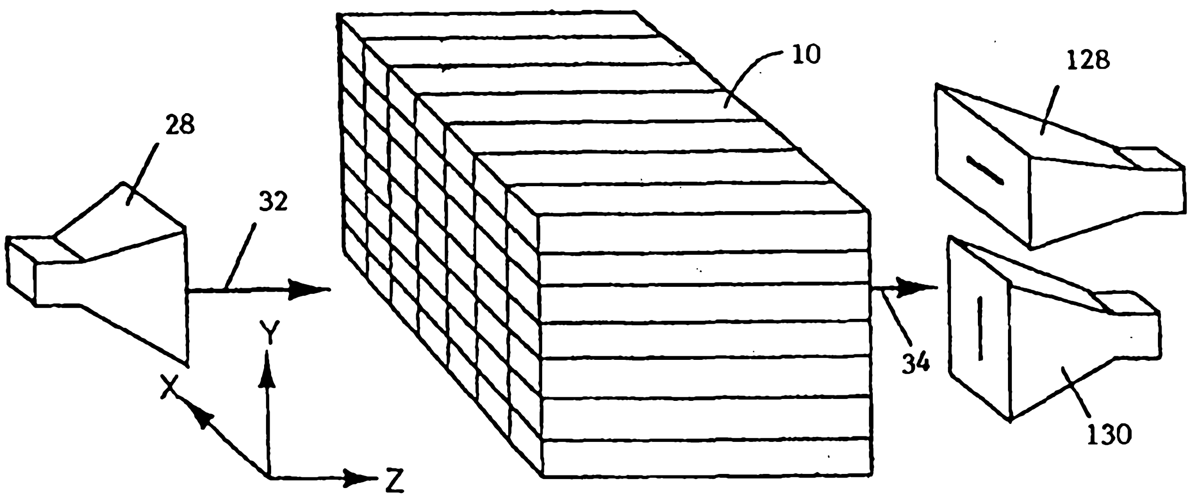


(57) Abstract

A device for measuring the moisture content of a module of material, including: a source (28), for producing a microwave radiation source beam, the source being located on one side of the module (10); at least one microwave antenna (128, 130) located on an opposing side of the module for receiving an exit beam and for producing an antenna signal; an attenuation unit for measuring an attenuation of the antenna signal; a phase shift determiner for determining a phase shift of the source beam and the antenna signal, the phase shift determiner including: a raw phase shift measurer for determining a raw phase shift of the source beam and the antenna signal; and a phase region determiner for determining a phase region of the raw phase shift from the attenuation and producing a corrected phase shift; and a moisture determiner for determining a moisture content of the module from the corrected phase shift and the attenuation.

APPLICATION FOR PATENT

Title: DEVICE AND METHOD FOR DETERMINING THE MOISTURE CONTENT OF MATERIAL

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to a device and method for determining the moisture content of material with multiple layers and, more particularly, to a device and method for determining the moisture content of non-homogeneous material.

Many different types of synthetic and organic material are the basis for the construction of many different manufactured products. These materials must be gathered, transported and stored before being used in the manufacturing process. The manufacturing process itself may require multiple procedures, first to prepare the raw material, and then to use the processed material in the formation of the actual product. Many of these procedures are dependent upon the moisture content of the material. If the moisture content is too high, for example, the material may decompose during storage and transportation, before it can be used. If the moisture content is too low, processing and use of the material may be difficult.

Synthetic and organic materials whose behavior depends upon their moisture content include tobacco, cotton, paper, processed wood, tea and synthetic fibers. As an example, cotton can be considered, although it will be appreciated that similar examples could be given for any of the above materials.

Raw cotton is a mixture of seeds and cotton fibers, which must be processed to separate the desired cotton fibers from the seeds. A cotton gin is used to separate the fibers from the seeds. In order for the gin to operate effectively, the moisture of the cotton fibers must be controlled during this processing. If the moisture content of the cotton fibers is too high, the fibers will tend to form wads which adhere to the cotton gin during processing, and which decompose more readily in storage. If the moisture content of the fibers is too low, the fibers will tend to generate static electricity and cling to metal surfaces. Fibers with low moisture content are also weaker, breaking more frequently.

The optimum moisture content of the cotton fibers is from 6.5 to 8%. However, the raw cotton can have a moisture content ranging from less than 3% to more than 20%. Thus, as the cotton gin processes the cotton, it must control the moisture content of the fibers to compensate for the widely varying moisture content of the raw cotton. Effective moisture control depends upon accurate measurement of the moisture content of the cotton.

Such measurements may be performed using microwave radiation. Typically, a microwave radiation source is located on one side of the cotton module, and an antenna is located on the opposite side of the cotton module. The radiation source beam is transmitted through a portion of the module and is received by the antenna, which then produces a signal. This signal is used to determine the moisture content of that portion of the module.

However, such measurements are difficult to perform, because of the size and internal structure of the raw material. Raw cotton is typically transported in massive modules. On average, each module has a width of 3 m, a height of 3 m and a length of 6 m, and a weight of 8 tons. Each module has many layers of material. Usually, these layers are somewhat loose, although they can be pressed together and bound by metal or plastic bars. Thus, a single measurement of the moisture content of the entire module is not physically possible. However, if the moisture content of only a portion of the module is measured, the moisture content of the entire module cannot be accurately determined from a single measurement because the moisture content through the module may vary from one point to another by approximately 5%. Thus, multiple measurements are required which do not damage the material itself.

The internal structure of the module itself presents difficulties. The layers of the raw cotton within the module frequently are not parallel, which can artifactually alter the behavior of the transmitted beam, and hence the apparent moisture content of the bale. Thus, the internal structure of the module must be compensated for during calculation of the moisture content of the material.

Furthermore, many types of modules can be used for transporting and storing raw cotton. Raw cotton can be transported and stored in cases. The internal structure of the case is typically less organized, leading to even greater inhomogeneities of material, and potentially causing even greater measuring artifacts. Cotton can also be transported and stored in bales. On average, each bale has a width of 0.5 m, a height of 0.7 m and a length of 1.4 m, and a weight of 250 Kg. Each bale has many layers of material which are pressed together and bound by metal or plastic bars. Thus, the internal structure of the bale is different from that of the case, so that a moisture measuring device which included compensation for the non-parallel layers of the bale would need different signal processing to compensate for the looser structure of the case.

Of course, cotton is not the only material to be transported, stored and processed. As mentioned above, tobacco, paper, processed wood, tea and synthetic fibers are also necessary synthetic and organic materials which form the basis of many different products. Each of these materials may also be transported and stored in several different forms, such as bale and case. The moisture content of each can affect processing, storage and manufacture. Furthermore, each of these materials forms different structures. That is, a bale of tobacco may have a very different internal structure from a bale of cotton. Thus, a moisture measuring device must be able to compensate for the effect of all of these different types of structures on the measured moisture content.

Unfortunately, no such moisture measuring device is known in the prior art. U.S. Patent No. 4,578,998, for example, is designed to measure the moisture content of sheet material. However, no mention is made of compensation for the layers of material being non-parallel. Furthermore, such a device would not be suitable for material which is not organized into such structured layers, such as cotton cases.

U.S. Patent No. 2,659,860 is designed to measure the moisture content of bales of material, by directing a microwave beam through the bale and receiving the beam with an antenna, which generates a signal. The moisture content of the bale is then determined from this signal. During this measurement, the bale must remain stationary between the source of the beam and the antenna, as described in column 5, lines 4-7. Furthermore, the bale must be carefully placed, so that the beam passes between the metal tie bars of the bale. The placement of the beam is also crucial because only a single measurement of the moisture content of the bale is made. However, the moisture content of the bale can differ by as much as five percent between two locations separated by only 2 cm, due to locally non-homogeneous material within the bale. Thus, the single measurement may not accurately reflect the overall moisture content of the bale. Furthermore, since the device does not include conveying means, or any means for making continuous or continual measurements, on a practical level making multiple measurements of the moisture content of a bale would be very difficult, since the bale would need to be manually moved for each new measurement. Finally, no mention is made of compensation for the layers of material being non-parallel, or indeed for the material not being organized into layers at all.

There is thus a widely recognized need for, and it would be highly advantageous to have, a device for measuring the moisture content of a unit of material, which can compensate for the internal structure of the unit of material, or lack thereof, which can make multiple measurements in order to determine the average moisture content of the entire unit of material, and which is capable of adjusting such measurements for the material itself.

SUMMARY OF THE INVENTION

According to the present invention there is provided a device for measuring the moisture content of a module of material, the module featuring a structure, the device having:

(a) a source of microwave radiation for producing a microwave radiation source beam, at least a portion of said source being located on one side of the module, such that at least a portion of said source beam is able to pass substantially completely through a portion of the module to form a passed source beam;

(b) at least one microwave receiving antenna located on an opposing side of the module, each said receiving antenna being spatially separated from said source such that said source beam must travel on a path selected from the group consisting of through the module and across the module, each said receiving antenna receives an exit beam and each said receiving antenna produces an antenna signal, said exit beam being said source beam after a transition from said source to said antenna, such that at least a portion of said exit beam is said passed source beam;

(c) a conveyor for conveying the module between said source and each said receiving antenna, such that a plurality of antenna signals, a plurality of source beams and a plurality of exit beams are produced, for generating a plurality of moisture measurements;

(d) an attenuation unit for receiving a first portion of each of said plurality of antenna signals and for measuring an attenuation of each of said plurality of antenna signals;

(e) a phase shift determiner for receiving a portion of each of said plurality of said source beams and a second portion of each of said plurality of antenna signals and for determining a phase shift between each of said plurality of said source beams and each of said plurality of antenna signals, said phase shift determiner including:

(i) a raw phase shift measurer for determining a raw phase shift of each of said plurality of said source beams and each of said plurality of antenna signals; and

(ii) a phase region determiner for determining a phase region of said raw phase shift from said attenuation of each of said plurality of said antenna signals and from an empirical curve determined for the structure of the module and the type of material, said empirical curve showing a relationship between said attenuation and said phase region, said phase region having a value in a range of from $2\pi(n-1)$ to $2\pi n$, n being determined by counting a number of cycles of said raw phase shift as the module is conveyed between said source and each said receiving antenna, such that said phase region determiner is able to produce a corrected phase shift according to said value of n; and

(f) a moisture determiner for determining a moisture content of the field director for manipulating a direction of an electric field of said source beam relative to the module, such that said direction of said electric field at least partially causes a magnitude of said attenuation and a magnitude of said phase shift.

Preferably the moisture determiner includes:

(i) a temperature sensor for determining a temperature of the module;

(ii) a module type input for inputting a type of the module; and

(iii) a normalizer for determining the moisture content from said temperature, said type, said corrected phase shift, and said attenuation.

Preferably the device further includes an averager for averaging said plurality of moisture measurements.

Preferably the material in the module has a substantially irregular structure.

Preferably the phase shift determiner receives a plurality of portions of said source beam and a plurality of portions of said plurality of antenna signals, such that said phase region of said raw phase shift is determined by counting a number of phase shift cycles, each phase shift cycle including values of said raw phase shift in a range from 0 to 2π.

Preferably the module is selected from the group consisting of bale and case, and the structure of the material is substantially irregular. Alternatively the module is selected from the group consisting of a bale and a case.

Preferably the module is said bale and the material is selected from the group consisting of tobacco, cotton, paper, processed wood, tea and synthetic fibers. Alternatively the module is said case and the material is selected from the group consisting of tobacco, cotton, paper, processed wood, tea and synthetic fibers.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention are herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIGS. 1A and 1B are illustrative examples of modules whose moisture can be measured by the present invention;

FIG. 2 is a block diagram illustrating one embodiment of the present invention;

FIG. 3 shows an example of a calibration curve used for calculating the moisture content of the module according to the present invention;

FIGS. 4A and 4B show a phase region curve of a preferred embodiment of the present invention;

FIGS. 5A-5F illustrate the relationship between the direction of the electrical field of the source beam relative to the module and the attenuation and phase shift of the antenna signal;

FIG. 6 illustrates a truck for conveying the device of Figure 2;

FIGS. 7A-7C illustrate another embodiment of the present invention; and

FIG. 8 illustrates the behavior of the antenna signal of the embodiment of Figures 7A and 7B.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a method and a device which can be used to measure the moisture content of a module of material.

The principles and operation of a method and a device according to the present invention may be better understood with reference to the drawings and the accompanying description.

Referring now to the drawings, Figures 1A and 1B are illustrative examples of modules whose moisture can be measured by the present invention. Figure 1A shows a module **10** which is a bale **12**. Bale **12** consists of pressed layers of material **14**, optionally held together with at least one tie bar **16**. Tie bar **16** can be made of plastic or metal. Layers **14** can be any synthetic or organic material, including, but not limited to, tobacco, cotton, paper, processed wood, tea and synthetic fibers. For the purposes of measuring the moisture content of bale **12**, bale **12** can be divided into at least one, and preferably a plurality, of areas **16**. Each area **16** includes at least one measurement point **18**, and preferably a plurality of measurement points **18**. At each measurement point **18**, the moisture content of that portion of bale **12** is determined (see Figure 2 below).

Figure 1B illustrates a module **10** which is a case **20**. Case **20** does not have defined layers, unlike bale **12**. However, case **20** can also be divided into at least one, and preferably a plurality, of areas **22**. Furthermore, each area **22** can also be subdivided into at least one, and preferably a plurality, of measurement points **24**. At each measurement point **24**, the moisture content of that portion of case **20** is determined (see Figure 2 below).

Figure 2 shows a device according to one embodiment of the present invention. Device **26** includes a microwave radiation source **28**, shown on one side of module **10**. Microwave radiation source **28** preferably includes at least one source antenna **30** for transmitting a source beam **32**. Source beam **32** is directed through module **10**, and passes out of module **10** as an exit beam **34**. Exit beam **34** is received by at least one receiving antenna **36**. Receiving antenna **36** is located on a substantially opposing side of module **10** relative to source antenna **30**.

After receiving antenna **36** has received exit beam **34**, receiving antenna **36** produces an antenna signal **38**. Antenna signal **38** then goes to an attenuation unit **40**. Attenuation unit **40** includes an attenuation measurer **42**, which measures the attenuation of antenna signal **38**. As source beam **32** passes through module **10**, source beam **32** is attenuated. The extent of this attenuation is determined by the elementary mass, which is the mass of the material of module **10** encountered by source beam **32**, and by the moisture content of the material of module **10** encountered by source beam **32**. Thus, attenuation measurer **42** is actually measuring the extent to which source beam **32** is attenuated by passing through module **10**.

At least a part of antenna signal **38** also goes to a phase shift determiner **44**, which determines the phase shift of antenna signal **38**. This phase shift is actually the phase shift caused by source beam **32** passing through module **10**, so that the phase shift is the difference between the phase of source beam **32** and the phase of exit beam **34**. The attenuation and the phase shift are determined according to the following equations:

$$A = 8.68 \alpha l$$

l being length of module **10**, α being the attenuation factor for module **10**.

$$P = (\beta - \beta_0) l$$

β and β_0 being phase factors for module **10** and air, respectively.

The attenuation and the phase shift of antenna signal **38** are then used by a moisture determiner **46** to determine the moisture content of module **10**.

Moisture determiner **46** uses the following equations to determine the moisture content of module **10**. In these equations, A is attenuation, P is phase shift, W is moisture content, and M is the elementary mass of module **10**. Equations 1 and 2 are integrated to produce equations 3 and 4. The moisture content, W, is then calculated.

$$dA = \frac{\partial A}{\partial W} dW + \frac{\partial A}{\partial m} dm$$

$$dP = \frac{\partial P}{\partial W} dW + \frac{\partial P}{\partial m} dm$$

$$A = \frac{\partial A}{\partial W} W + \frac{\partial A}{\partial m} m$$

$$P = \frac{\partial P}{\partial W} W + \frac{\partial P}{\partial m} m$$

A number of optional features can be added to device **26** in order to increase the accuracy of moisture measurements. Preferably, attenuation unit **40** includes an attenuator **48**. The function of attenuator **48** is to attenuate antenna signal **38**, so that antenna signal **38** becomes an attenuated antenna signal **50**. A coupler **52** then splits attenuated antenna signal **38** into two portions. A first portion of attenuated antenna signal **50** goes to phase shift determiner **44**. A second portion of attenuated antenna signal **50** preferably goes to attenuation measurer **42**. Attenuation measurer **42** preferably determines the difference between the amplitude of attenuated antenna signal **50** and the amplitude of a constant reference signal **54**. The difference between these two amplitudes determines the extent to which attenuator **48** attenuates antenna signal **38**, so that the attenuation of antenna signal **38** is kept substantially constant. Such constancy is required for the proper operation of phase shift determiner **44** (see below).

As noted above, phase shift determiner **44** determines the difference, or phase shift, between the phase of source beam **32** and the phase of exit beam **34**. Phase shift determiner **44** preferably includes a mixer **56**, which outputs a signal which is proportional to the phase shift between source beam **32** and exit beam **34**, as represented by antenna signal **38**. In order for mixer **56** to receive a portion of source beam **32**, microwave radiation source **28** preferably includes a second coupler **58**, for splitting source beam **32** into two portions. A first portion of source beam **32** is directed through module **10** as described above. A second portion of source beam **32** is directed to mixer **56**.

Phase shift determiner **44** preferably also includes a signal phase shift measurer **60**. Signal phase shift measurer **60** measures the phase shift between source beam **32** and exit beam **34** from the signal output by mixer **56**. In order to obtain the most accurate moisture content measurements, phase shift measurer **60** can optionally include a number of features designed to compensate for inaccuracies in the measurement of the phase shift. These features include a raw phase shift measurer **62**, which determines the raw phase shift. Next, a phase region determiner **64** determines the phase region of the raw phase shift from the attenuation of antenna signal **38** and produces a corrected phase shift. As measured directly from source beam **32** and exit beam **34**, as represented by antenna signal **38**, the phase shift can only vary from 0 to 2π. However, the correct phase actually lies between $2\pi(n-1)$ and $2\pi n$, which can be from 0 to 2π, but which could also be from 4π to 6π, for example. Thus, the phase region, or the value of n, must be determined. Such a determination is made using an empirical phase region curve, as shown in Figure 4 below, which relates the attenuation of antenna signal **38** to the phase region. The correct phase shift is then given to moisture determiner **46**.

In order for the phase shift measurement to be accurate, the attenuation of antenna signal **38** must be kept substantially constant. Otherwise, the comparison between source beam **32** and antenna signal **38** will be artifactually altered by the attenuation of antenna signal **38**.

As noted above, once the phase shift and the attenuation have been measured, moisture determiner **46** determines the moisture content of module **10**. Moisture determiner **46** preferably includes a temperature sensor **66** for measuring the temperature of module **10**. The type of module **10** is preferably input into moisture determiner **46** by a module type input **68**. The type of module **10** is determined by the material of module **10**, and by the form of module **10**: for example, bale **12** or case **20**. Finally, moisture determiner **46** preferably includes a normalizer **70**. Normalizer **70** preferably includes an empiric function **72**. Empiric function **72** determines the moisture content of module **10** from the temperature and type of module **10**, and from the attenuation and phase shift calculated above.

The above description has treated the measurement of the moisture content of module **10** as though a single moisture measurement was made. However, preferably a plurality of such measurements are made and averaged by an averager **74**. As described in Figure 1, bale **12** can be divided into preferably a plurality of areas **16**. Each area **16** is preferably subdivided into a plurality of measurement points **18**. At each measurement point **18**, the moisture content of that portion of bale **12** is determined according to the above description, so that a plurality of measurements are made and averaged by averager **74**. A similar argument can be made for case **20**, areas **22** and measurement points **24**. These averaged measurements are then preferably compared to a calibration curve, of the type shown in Figure 3, in order to obtain the moisture content of module **10**. Optionally, in order to facilitate such multiple measurements, device **26** can include a conveyor, such as a conveyor belt (not shown) or a truck (not shown, see Figure 6) to convey bale **12** between microwave radiation source **28** and receiving antenna **36**.

Optionally, microwave radiation source **28** can also include a second source antenna **76**. Also optionally, device **26** can also include a second receiving antenna **78**. Optionally, an oscillator **80** controls a first switch **82** and a second switch **84**. These optional features are used to measure the moisture content of module **10** in two parts when module **10** is too tall for a single measurement. First, oscillator **80** flips first switch **82** so that first source antenna **30** directs source beam **32**, and second switch **84** so that first receiving antenna **36** produces antenna signal **38**. This particular configuration is shown in Figure 2, and is used to measure the moisture content of the lower portion of module **10**. Next, oscillator **80** flips first switch **82** so that second source antenna **78** directs source beam 32. Oscillator **80** also flips second switch **84** so that second receiving antenna **78** produces antenna signal 38. Now, the moisture content of the upper portion of module **10** is measured.

Microwave radiation source **28** can also optionally include a number of features which are designed to maximize the sensitivity of the moisture content measurements, by manipulating the direction of the electric field density of source beam **32** (see also Figures 5A-5F). Microwave radiation source **28** can include an electric field director **86**. Electric field director **86** determines a direction of the electric field density of source beam 32 relative to module **10**, such that the direction of the electric field density partially determines the magnitude of the attenuation and the magnitude of the phase shift. If module **10** has layers **14** (not shown), substantially the maximum attenuation and substantially the maximum phase shift of antenna signal **38** is obtained when the electric field density is substantially perpendicular to layers **14** (not shown) of module **10**. When the electric field density is substantially parallel to layers **14** (not shown) of module **10**, substantially the minimum attenuation and the minimum phase shift of antenna signal **38** is obtained. Even if module **10** does not have layers **14**, changing the direction of the electric field density will still alter the attenuation and phase shift of antenna signal **38**, according to the orientation of the material being measured relative to the electric field density. Electric field director **86** determines the direction of the electric field density according to feedback from attenuation measurer **42**. Thus, if the attenuation of antenna signal **38** is low, electric field director **86** can change the direction of the electric field density in order to compensate. Clearly, this has obvious advantages in maximizing the sensitivity and accuracy of the moisture measurements.

Figure 3 shows an illustrative example of a calibration curve **88**, showing the relationship between attenuation, in dB, on the Y-axis, and moisture content, as a percentage, on the X-axis. Each calibration curve **88** is empirically determined for each type of module **10** (for example bale or case), and for each type of material (for example, cotton or tobacco). The moisture content of module **10** is then determined from calibration curve **88**. A more complete description of these curves and their derivation can be found in "Theoretical and Experimental Investigation of Microwave Moisture Measurement of Materials" by A. Greenwald, *FAN*, Uzbekistan, 1982.

Figure 4A shows a graph of a phase region curve **90** as mentioned above. Phase region curve **90** is an empirical curve of the attenuation of antenna signal **38** on the X-axis, and the phase region on the Y-axis. As an example, if the attenuation is equal to A_1, phase region curve **90** shows that the phase region lies between 0 and 2π. Different phase region curves must be determined for each material and type of module **10**.

In order to use this curve, the attenuation and phase shift of antenna signal **38** are preferably measured as module **10** is conveyed between source antenna **30** and receiving antenna **36**. For example, a first measurement could be made before the leading edge of module **10** enters the region between source antenna **30** and receiving antenna **36**, a second measurement could be made as the leading edge of module **10** enters that region, and a third measurement could be made when module **10** is aligned between source antenna **30** and receiving antenna **36**. The relationship between these multiple measurements and the phase region is shown in Figure 4B. At the top is a diagram of module **10** being conveyed between source antenna **30** and receiving antenna **36**. At the bottom is a graph of the relationship between the increasing attenuation as module **10** becomes aligned between source antenna **30** and receiving antenna **36**, and the phase shift, which is based upon empirical phase region curve **90** of Figure 4A. As the phase shift cycles between 0-2π while module **10** is conveyed between source antenna **30** and receiving antenna **36**, the number of cycles can be counted and the phase region can be determined.

Figures 5A-5F illustrate the relationship between the direction of the electric field density of the source beam relative to the module and the attenuation and phase shift of the antenna signal. Figure 5A shows an electric field density **92** and a magnetic field density **94**. Electric field density **92** is perpendicular to layers **14** of module **10**. In Figure 5B, electric field density **92** has been rotated by about 45 degrees. In Figure 5C, electric field density **92** has been rotated by about 90 degrees, relative to Figure 5A. Now electric field density **92** is parallel to layers **14** of module **10**. Figures 5D-5F show the effect of these shifts in the direction of electric field density **92** on attenuation

96 and phase shift 98 of antenna signal 38. In Figure 5D, both attenuation 96 and phase shift 98 of antenna signal 38 are at substantially a minimum level, because electric field density 92 is perpendicular to layers 14, as shown in Figure 5A. In Figure 5E, both attenuation 96 and phase shift 98 of antenna signal 38 have increased, due to the rotation of electric field density 92 as shown in Figure 5B. Finally, in Figure 5F, both attenuation 96 and phase shift 98 of antenna signal 38 are at substantially a maximum level, because electric field density 92 is parallel to layers 14, as shown in Figure 5C.

Optionally, device 26 can be mounted on a truck 100, as shown in Figure 6. Microwave radiation source 28 and receiving antenna 36 are both mounted on truck 100. Truck 100 then moves past module 10, so that module 10 passes between microwave radiation source 28 and receiving antenna 36. In this manner, a plurality of moisture measurements of module 10 can be made and averaged, as described above.

Figures 7A-7C illustrate another embodiment of the present invention. Figure 7A is a schematic illustration of another embodiment of device 26, similar to the one shown in Figure 2, except that receiving antenna 36 is preferably a circularly polarized antenna. Furthermore, a conveyor 102, such as a conveyor belt, moves module 10, shown here as bale 12, between source of microwave radiation 28 and receiving antenna 36, such that source beam 32 passes through a portion of bale 12, and exits bale 12 as an exit beam 34. Since conveyor 102 is moving module 10, source beam 32 can pass through a plurality of portions of bale **12**. Thus, if there are *i* such portions along bale **12**, *i* moisture measurements can be made. Exit beam **34** is received by receiving antenna **36**, which then produces an antenna signal **38**.

In this embodiment, antenna signal **38** is then examined by a bale alignment determiner **104**. Bale alignment determiner **104** then determines the alignment of bale **12** relative to source beam **32** and receiving antenna **36**. Bale alignment determiner **104** includes a leading edge transition determiner **106**, an interval timer **108** and a trailing edge transition determiner **110**. Leading edge transition determiner **106** detects when a leading edge of bale **12** has passed radiation source **28**, and produces a leading edge transition signal. Interval timer **108** receives the leading edge transition signal and produces an alignment signal, such that alignment signal is produced when bale **12** is correctly aligned between microwave radiation source **28** and receiving antenna **36**. Trailing edge transition determiner **110** determines when the trailing edge of bale **12** passes microwave radiation source **28**, and produces a trailing edge transition signal.

A moisture determiner **112** then determines the moisture content of bale **12** from the alignment signal. Moisture determiner **112** includes a background moisture content measurer **114**, which measures the background moisture content of antenna signal **38** after receiving the trailing edge transition signal. This background moisture content includes both the ambient moisture content, from source beam **32** passing through the air, and artifacts caused by device **26** itself, such as misalignment of source beam **32** relative to bale **12** and movement of receiving antenna **36** from the correct position relative to bale **12**. Moisture determiner **112** also includes a filter **116** for producing a corrected signal by removing the background moisture content from the alignment signal.

Preferably, moisture determiner **112** also includes a tie bar suppressor **118**. If source beam **32** contacts a tie bar **16** as source beam **32** goes through bale **12**, antenna signal **38** can be affected, potentially resulting in an incorrect moisture measurement. Tie bar suppressor **118** removes any such effects from the corrected signal, and produces a further corrected signal. Preferably, this corrected signal then goes to a normalizer **120**. Normalizer **120** compensates for effects caused by temperature, mass and length of bale **12**, thus normalizing the corrected signal. Such normalization is performed by the following equations:

W_{Xi} = the i^{th} moisture measurement in the X-channel,

W_{Yi} = the i^{th} moisture measurement in the Y-channel,

W_0 = the nominal mass of the bale $\approx$ 250 Kg,

W_c = the actual measured mass of the bale,

L_0 = the nominal length of the layers taken along the width of the bale,

L_c = the actual length of the layers taken along the width of the bale,

T_0 = the base temperature of the cotton fibers (35°C) an

T_c = the temperature of the cotton fibers in the current slice,

it may be shown that:

$$W_{x_i}^{I} = \frac{T_o - T_c}{10} + W_{x_i}$$

$$W_{y_i}^{I} = \frac{T_o - T_c}{10} + W_{y_i}$$

$$W_{x_i}^{II} = W_{x_i}^{I} \left(\frac{W_o}{W_c}\right)$$

$$W_{y_i}^{II} = W_{x_i}^{I} \left(\frac{W_o}{W_c}\right)$$

$$W_{x_i}^{III} = W_{x_i}^{II} \left(\frac{L_o}{L_c}\right)$$

$$W_{y_i}^{III} = W_{x_i}^{II} \left(\frac{L_o}{L_c}\right)$$

Finally, the normalized signal preferably goes to a mean moisture unit **122**, which determines the moisture content of bale **12**. Preferably, mean moisture unit **122** averages the moisture content of bale **12** over all *i* measurements of *i* portions of bale **12**.

Receiving antenna **36** can optionally include an amplitude determiner **124** and an attenuation determiner **126**. Amplitude determiner **124** determines an amplitude of exit beam **34**. Attenuation determiner **126** then produces an attenuated signal, by determining an attenuation of exit beam **34** from the amplitude of exit beam **34**. The attenuated antenna signal is then processed in a similar fashion as antenna signal **38**.

In the preferred embodiment shown in Figure 7B, source beam **32** is circularly polarized, and exit beam **34** has two mutually orthogonal components. One of these components is in the direction of the X-axis, and one component is in the direction of the Y-axis. For convenience, Figure 7C shows a partial illustration of device **26** according to Figure 7B, with X-, Y- and Z-axes illustrated.

Referring back to Figure 7B, each component is received by one of two linearly polarized microwave receiving antennas **128** and **130**, respectively. Each mutually orthogonal component is separately processed, similar to the above description in Figure 7A, so that there are two bale alignment determiners **104** and **132**. Moisture determiner **112** has two filters **116** and **134** for removing the background moisture component and producing a corrected signal. Preferably, two digital samplers **136** and **138** then produce a digitized signal from each component of the corrected signal. There is also preferably a component moisture computer **140** which then computes a moisture content of each mutually orthogonal component of the digitized signal.

Preferably, moisture determiner **112** also has a ratio determination unit **142** for determining a ratio of each of the moisture contents produced by component moisture computer **140**, according to the following equations:

$$W_{i_{x(meas)}} = W_{i_x}\cos\beta + W_{i_y}\sin\beta$$

$$W_{i_{y(meas)}} = W_{i_x}\sin\beta + W_{i_y}\cos\beta$$

$$K = \frac{W_{i_x}}{W_{i_y}}$$

where:

$W_{i_{x(meas)}}$ = measured moisture content in the X direction for the i^{th} area,

$W_{i_{y(meas)}}$ = measured moisture content in the Y direction for the i^{th} area,

W_{i_x} = maximum moisture content of the i^{th} area in the X-direction,

W_{i_y} = maximum moisture content of the i^{th} area in the Y-direction,

β = the angle of inclination of the layers to the X-direction,

K = the ratio of the maximum moisture values in the X and Y directions,

and

α_i = the measured ratio $W_{i_{x(meas)}} : W_{i_{y(meas)}}$.

A comparator **144** then compares the ratio with the predetermined constant K, which is obtained when layers in bale **12** are substantially parallel. If the ratio is substantially equal to K, a parallel layer moisture determiner **146** determines the moisture content of bale **12**. Otherwise, a non-parallel layer moisture determiner **148** determines the moisture content of bale **12** when the ratio is substantially not equal to the predetermined constant K.

Non-parallel layer moisture determiner **148** preferably determines the moisture content of bale **12** by using an empirical function

$$W = W_y + 3.2 \times 10^{-2} \frac{(\alpha - 1)}{K}$$

where W is the moisture content of the signal, W_y is the moisture content of one of the mutually orthogonal components which passed through bale **12** in a direction normal to layers, α is the ratio, and K is the predetermined constant.

Figure 8 illustrates the behavior of the antenna signal of the embodiment of Figures 7A and 7B. Antenna signal **38** starts at a generally low background level **150** which climbs to an initial higher level **152** at a time T_0 when bale **12** (not shown) enters the region between microwave radiation source **28** (not shown) and receiving antenna **36** (not shown). Antenna signal **38** then reaches a first artifactual peak **154** during time interval T_1, due to edge transition effects caused by the leading edge of bale **12** passing between microwave radiation source **28** (not shown) and receiving antenna **36** (not shown). During this time, a first portion of source beam **32** passes through bale **12** (not shown), and a second portion does not, causing these edge transition effects.

Once bale **12** (not shown) is correctly aligned between microwave radiation source **28** (not shown) and receiving antenna **36** (not shown), for example as in Figures 7A and 7B, antenna signal **38** goes to a steady level **156** during time interval T_2 and remains substantially constant during this time interval, except for fluctuations due to local inequalities in the moisture content and structure of bale **12**. During time interval T_2, the alignment signal is produced, and all moisture measurements of bale **12** are made. At time T_3, the trailing edge of bale **12** (not shown) starts to move past microwave radiation source **28** (not shown) and receiving antenna **36** (not shown), causing a second artifactual peak **158**, again due to edge transition effects caused by the trailing edge of bale **12**.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A device for measuring the moisture content of a module of material, the module featuring a structure, the device having:

(a) a source of microwave radiation for producing a microwave radiation source beam, at least a portion of said source being located on one side of the module, such that at least a portion of said source beam is able to pass substantially completely through a portion of the module to form a passed source beam;

(b) at least one microwave receiving antenna located on an opposing side of the module, each said receiving antenna being spatially separated from said source such that said source beam must travel on a path selected from the group consisting of through the module and across the module, each said receiving antenna receives an exit beam and each said receiving antenna produces an antenna signal, said exit beam being said source beam after a transition from said source to said antenna, such that at least a portion of said exit beam is said passed source beam;

(c) a conveyor for conveying the module between said source and each said receiving antenna, such that a plurality of antenna signals, a plurality of source beams and a plurality of exit beams are produced, for generating a plurality of moisture measurements;

(d) an attenuation unit for receiving a first portion of each of said plurality of antenna signals and for measuring an attenuation of each of said plurality of antenna signals;

(e) a phase shift determiner for receiving a portion of each of said plurality of said source beams and a second portion of each of said plurality of antenna signals and for determining a phase shift between each of said plurality of said source beams and each of said plurality of antenna signals, said phase shift determiner including:

   (i) a raw phase shift measurer for determining a raw phase shift of each of said plurality of said source beams and each of said plurality of antenna signals;

and

(ii) a phase region determiner for determining a phase region of said raw phase shift from said attenuation of each of said plurality of said antenna signals and from an empirical curve determined for the structure of the module and the type of material, said empirical curve showing a relationship between said attenuation and said phase region, said phase region having a value in a range of from $2\pi(n-1)$ to $2\pi n$, n being determined by counting a number of cycles of said raw phase shift as the module is conveyed between said source and each said receiving antenna, such that said phase region determiner is able to produce a corrected phase shift according to said value of n; and

(f) a moisture determiner for determining a moisture content of the module from said corrected phase shift and said attenuation.

2. A device as claimed in claim 1, wherein said attenuation unit includes:

(i) an attenuation measurer for measuring an amplitude of each of said plurality of antenna signals, for comparing each said amplitude to an amplitude of a reference signal of a constant amplitude, and for determining a difference between said constant amplitude of said reference signal and each said amplitude of each said antenna signal; and

(ii) an attenuator for attenuating each said antenna signal according to each said difference.

3. A device as claimed in either claim 1 or 2, wherein:

(a) said microwave radiation source includes:

(i) a first source antenna for producing and focussing said source beam such that said source beam passes through a lower portion of the module;

(ii) a second source antenna for producing and focussing said source beam such that said source beam passes through a upper portion of the module; and

(b) said at least one microwave receiving antenna is a first microwave receiving antenna and a second microwave receiving antenna, and said microwave receiving antennas include a switch, such that said first microwave receiving antenna produces a said antenna signal when said first source antenna produces and focusses said source beam, and said second microwave receiving antenna produces a said antenna signal when said second source antenna produces and focusses said source beam.

4. A device as claimed in either claim 1 or 2, wherein said microwave radiation source includes an electric field director for manipulating a direction of an electric field of said source beam relative to the module, such that said direction of said electric field at least partially causes a magnitude of said attenuation and a magnitude of said phase shift.

5. A device as claimed in any one of the preceding claims, wherein said moisture determiner includes:

(i) a temperature sensor for determining a temperature of the module;

(ii) a module type input for inputting a type of the module; and

(iii) a normalizer for determining the moisture content from said temperature, said type, said corrected phase shift, and said attenuation.

6. A device as claimed in any one of the preceding claims, further including:

(g) an averager for averaging said plurality of moisture measurements.

7. A device as claimed in any one of the preceding claims, wherein the material in the module has a substantially irregular structure.

8. A device as claimed in any one of the preceding claims, wherein said phase shift determiner receives a plurality of portions of said source beam and a plurality of portions of said plurality of antenna signals, such that said phase region of said raw phase shift is determined by counting a number of

phase shift cycles, each phase shift cycle including values of said raw phase shift in a range from 0 to 2π.

9. A device as claimed in any one of claims 1 to 8, wherein the module is selected from the group consisting of bale and case, and the structure of the material is substantially irregular.

10. A device as claimed in any one of claims 1 to 8, wherein the module is selected from the group consisting of a bale and a case.

11. A device as claimed in claim 10, wherein the module is said bale and the material is selected from the group consisting of tobacco, cotton, paper, processed wood, tea and synthetic fibers.

12. A device as claimed in claim 10, wherein the module is said case and the material is selected from the group consisting of tobacco, cotton, paper, processed wood, tea and synthetic fibers.

13. A device for measuring the moisture content of a module of material substantially as hereinbefore described with reference to figures 2, 3 and 6 or to figures 4A to 5F or to figures 7A to 8 of the accompanying drawings.

Dated this 25th day of May 2001
MALCAM LTD.
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent and
Trade Mark Attorneys of Australia

FIG. 1A

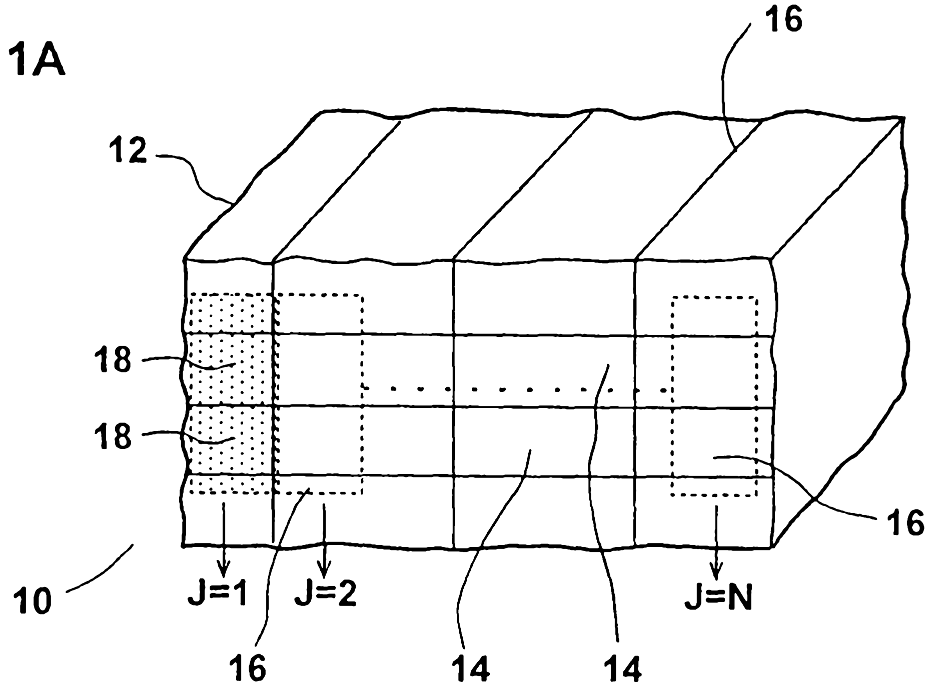
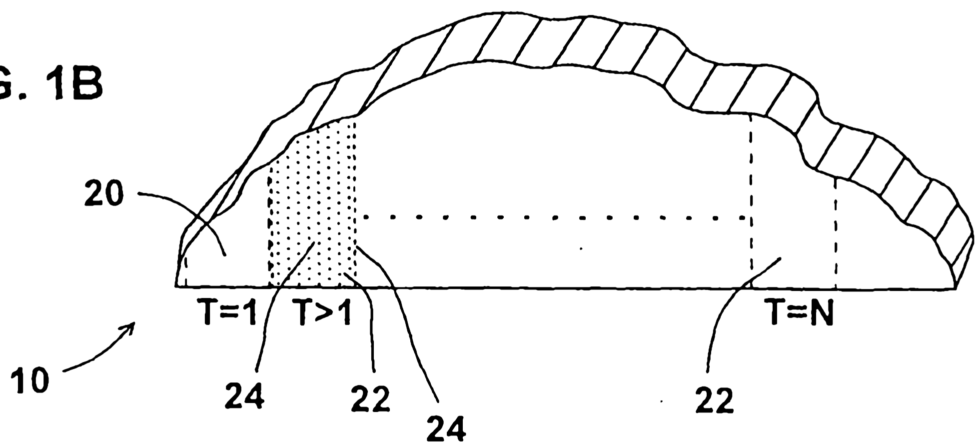


FIG. 1B



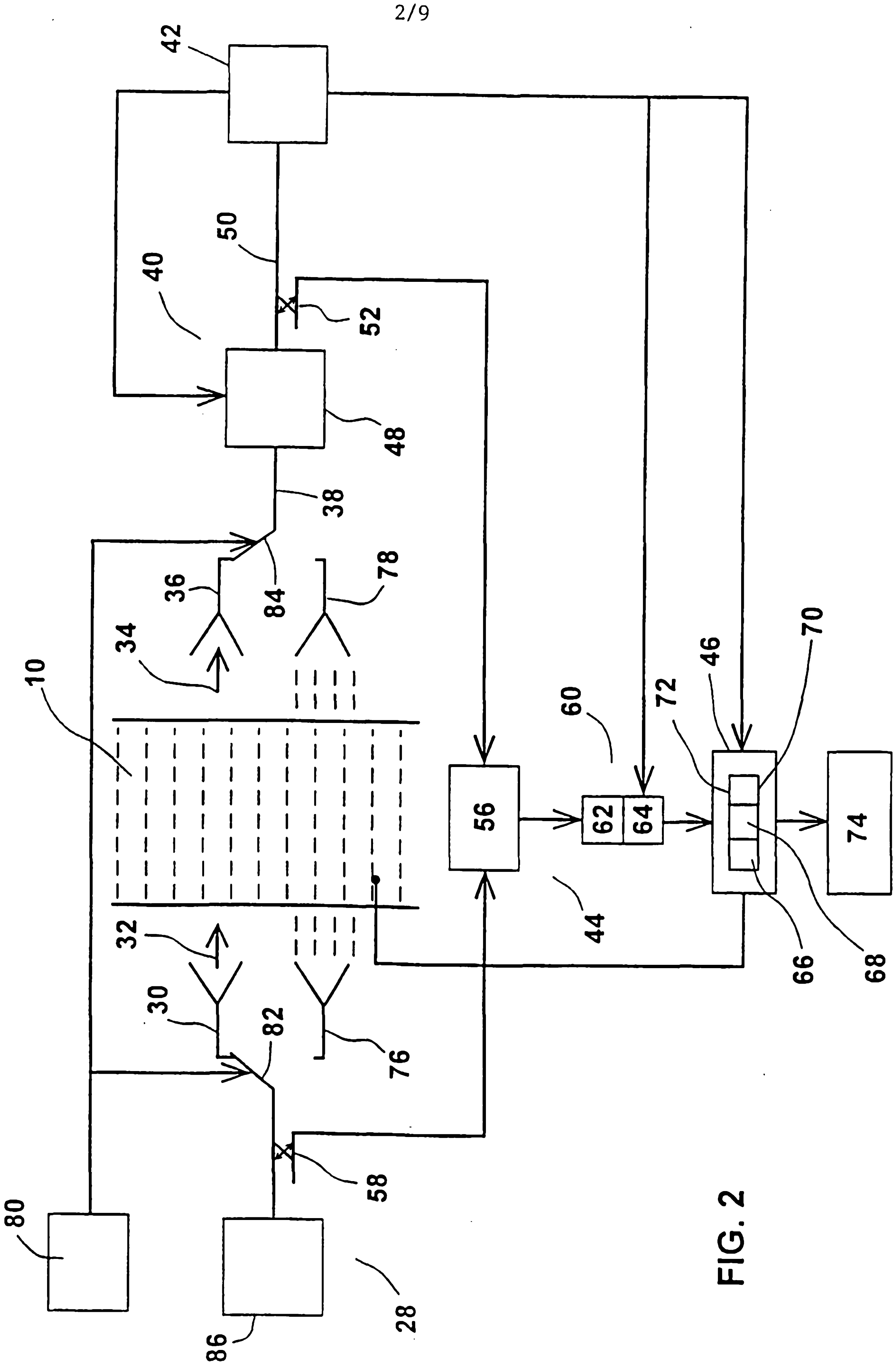

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FIG. 2

FIG. 3

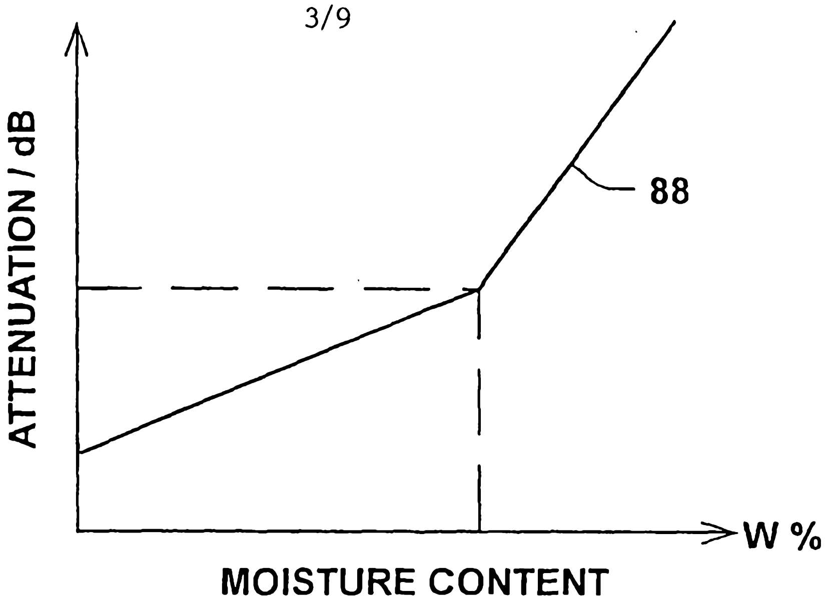
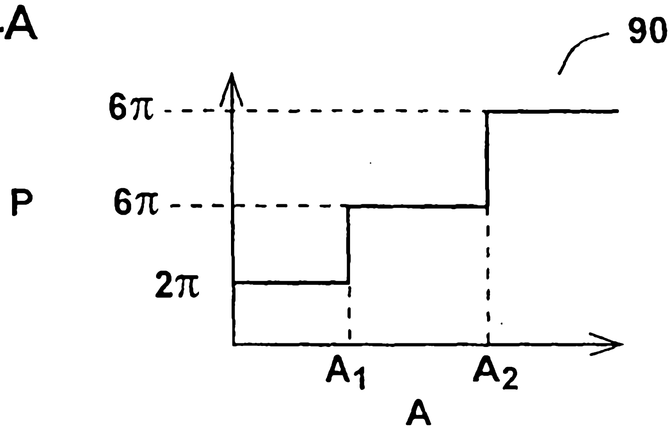


FIG. 4A



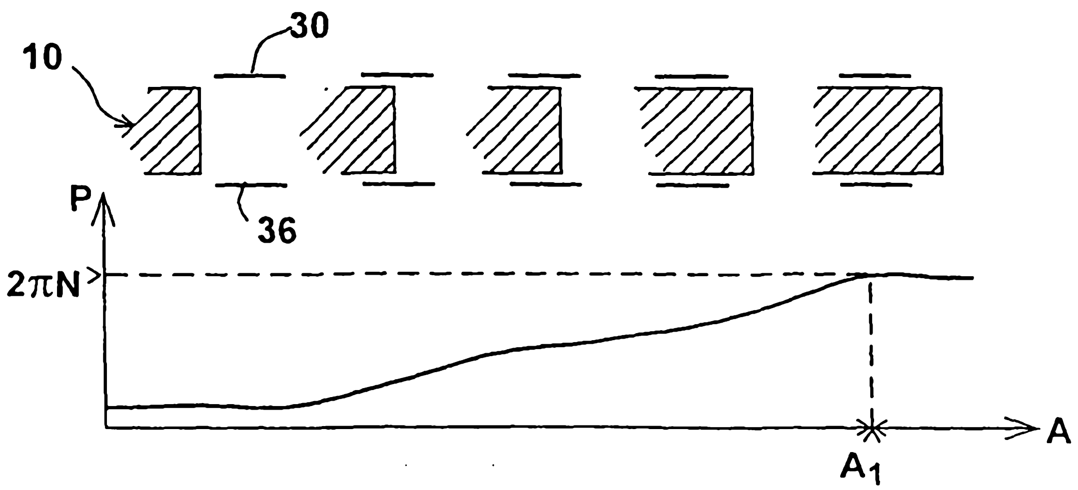


FIG. 4B

FIG. 5A

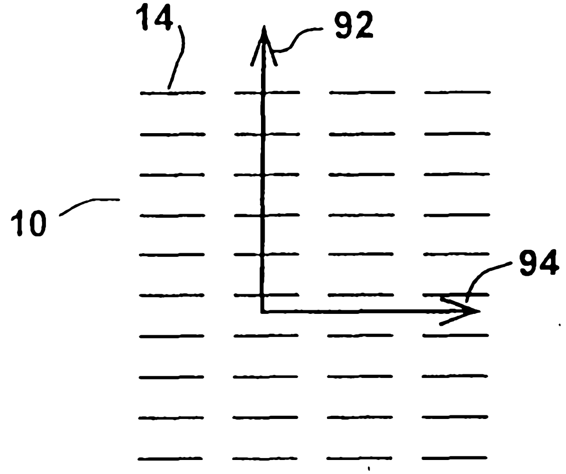


FIG. 5B

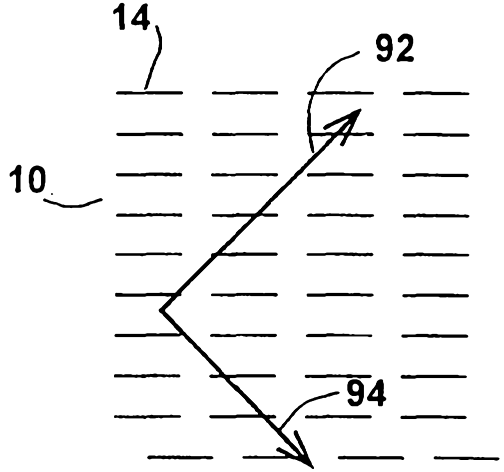
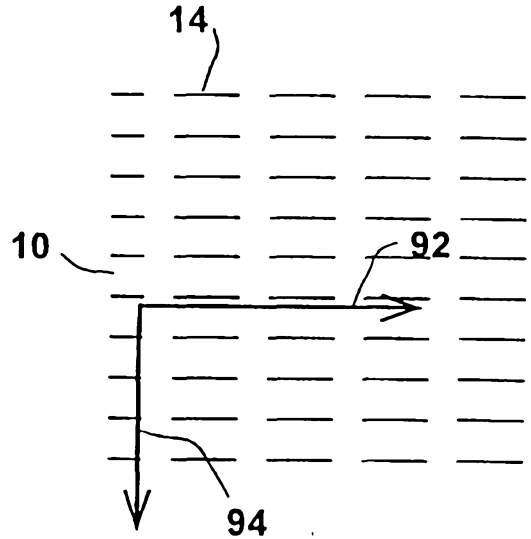


FIG. 5C



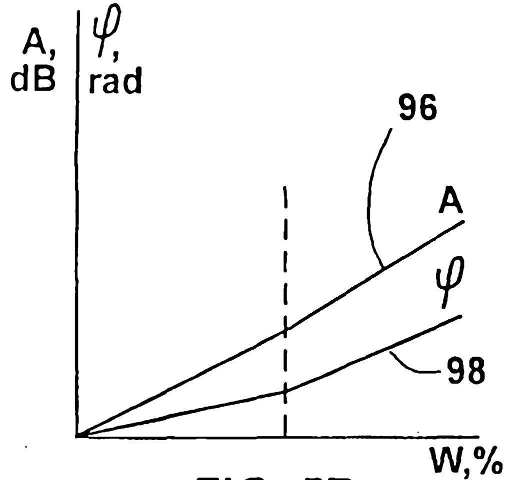


FIG. 5D

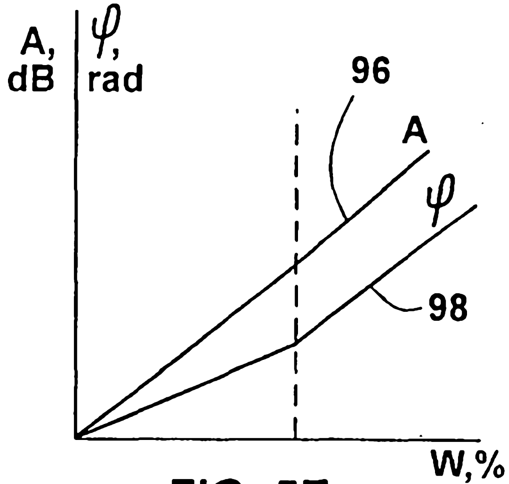


FIG. 5E

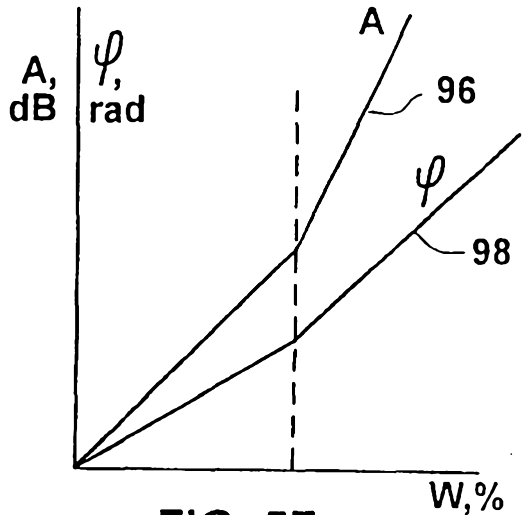


FIG. 5F

FIG. 6

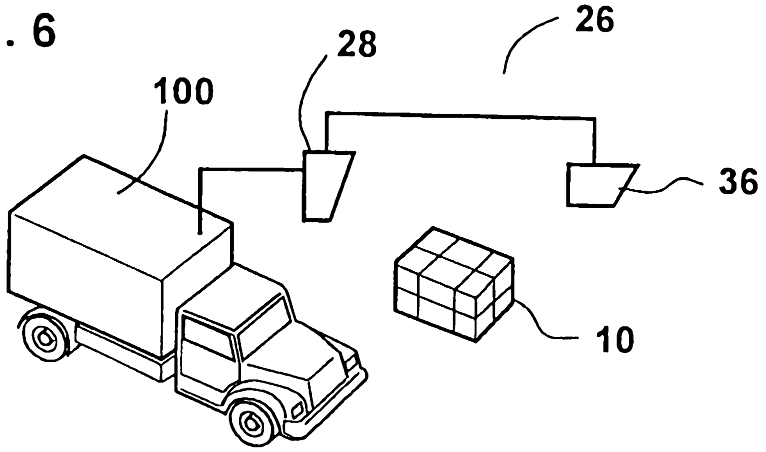


FIG. 7A

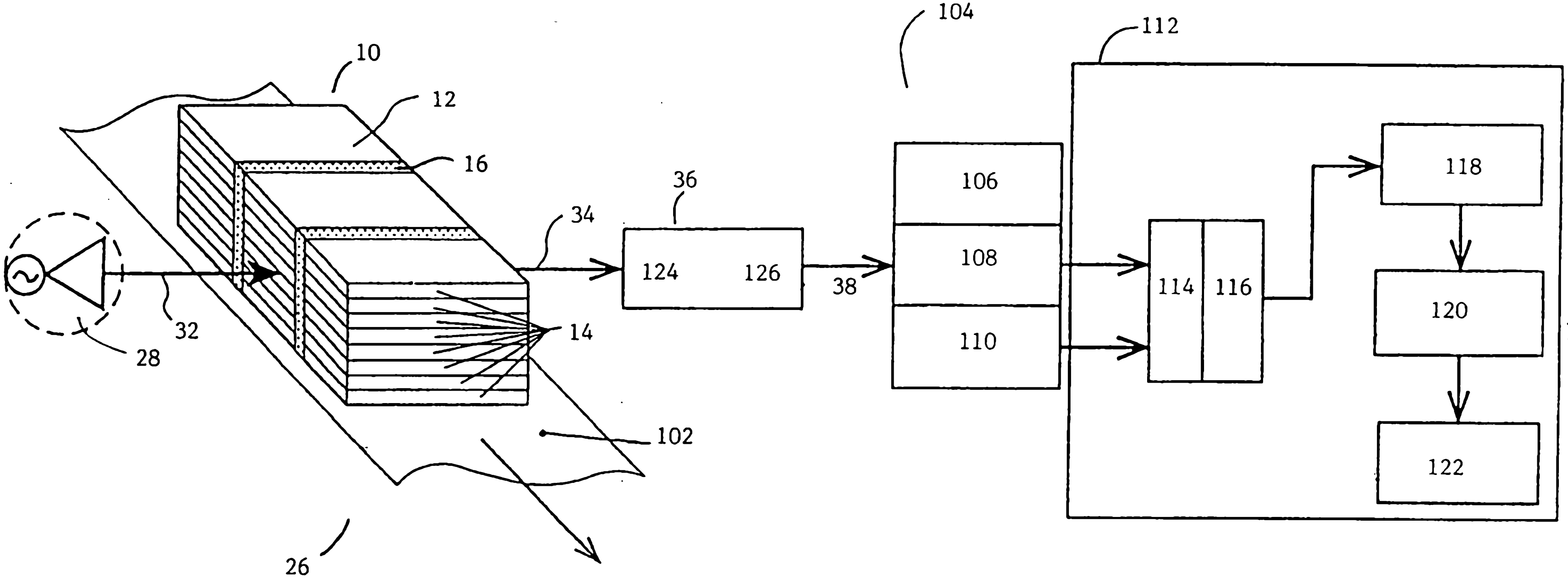

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FIG. 7B

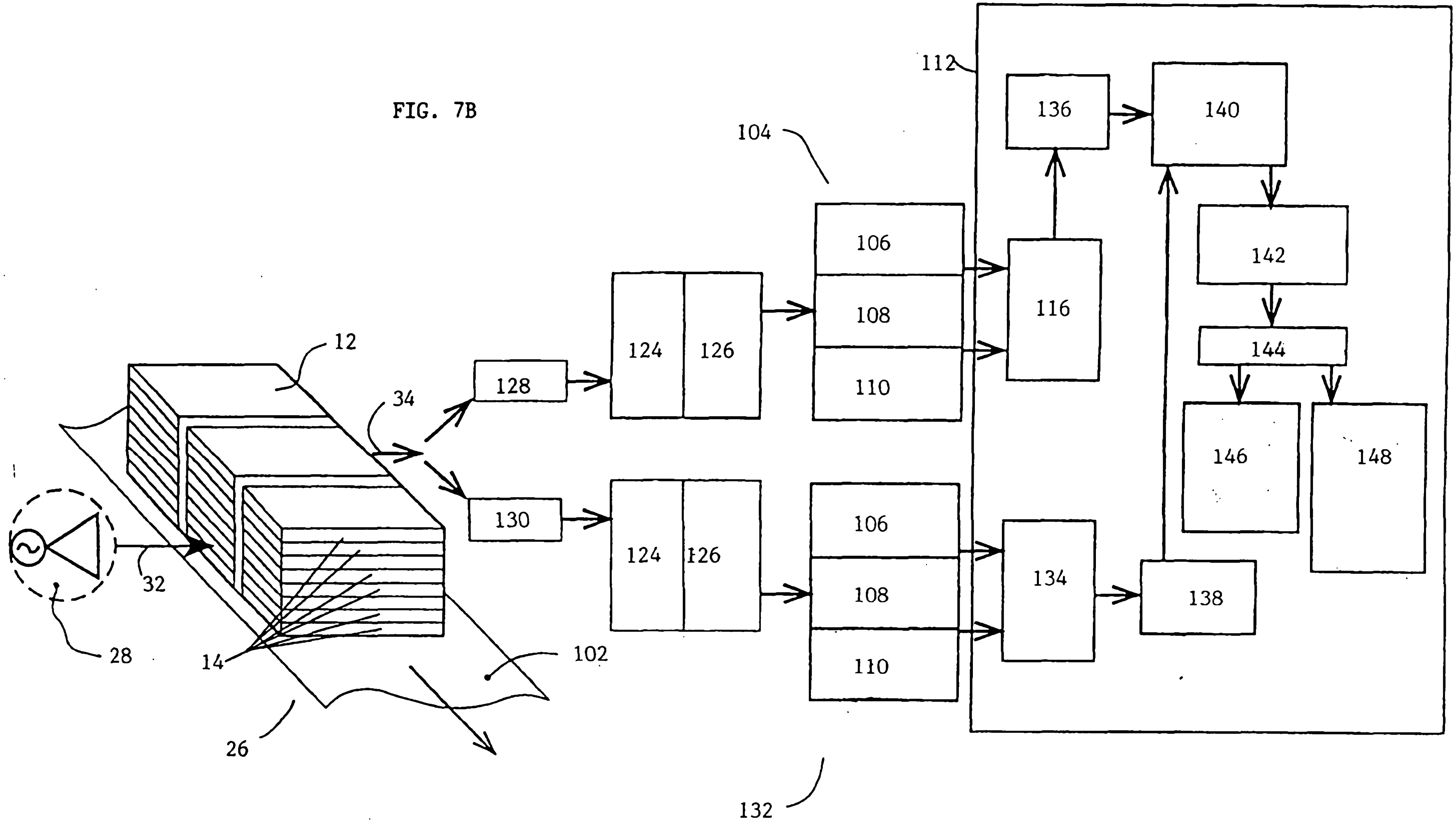
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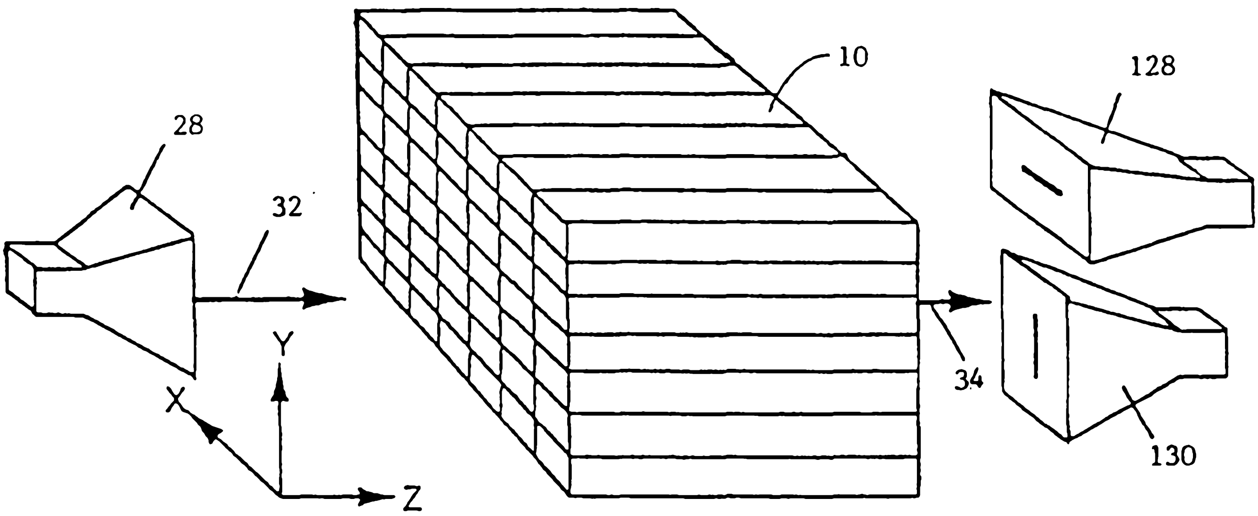
FIG. 7C



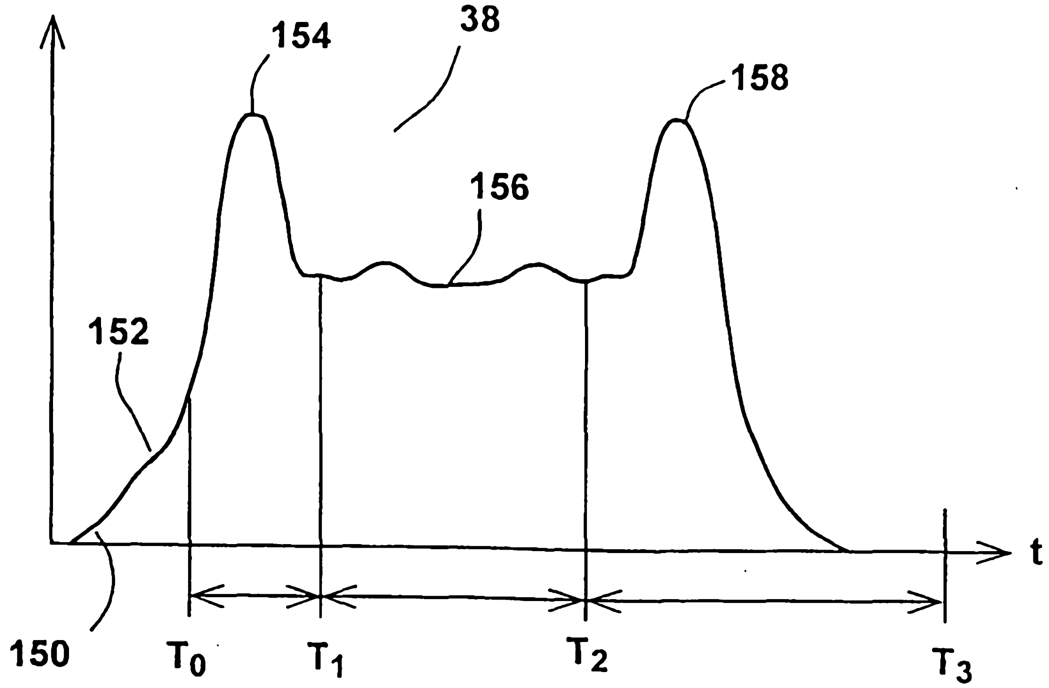


FIG. 8