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Novel Adjustable Microstrip Devices for Microwave Power Division and Impedance Matching

Elías de los Reyes, Javier García, David Marqués, Antonio Jara
Universidad Politécnica de Valencia Camino de Vera, s/n 46022 Valencia, Spain

Ruth de los Reyes
Microbiotech SL Avda Benjamin Franklin, 12;
CEEI: módulo 10 46980 Paterna (Valencia), Spain

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ABSTRACT

This paper describes the design and implementation of novel adjustable microstrip devices which made possible new methods for phase shifting, variable power division and adjustable impedance matching in the 2.45 GHz ISM band. This novel technology is more affordable and simpler to develop than other state of the art technologies described in this paper. The development of this technology took place in the frame of a degree project on energetic applications of microwaves for Microbiotech SL (MBT). These devices have been used for the proper power delivery of microwave energy to a sample material provided by Microbiotech SL. The presence of this material can modify the impedance of the applicator according to the relative permittivity of the sample and therefore reduce the amount of microwave energy delivered by the applicator to the medium. The adjustable impedance matching network made possible the total transfer of electromagnetic energy, providing a simple and versatile method for reducing return losses to a minimum regardless of the load presented to the transmission line. In the other hand, the variable power divider addressed a more common problem in microwave heating such as power flow control. It supposes an affordable approach, which may be useful in some researching scenarios. The mechanism is based on the sliding of microstrip lines over the conductors of a circuit. The sliding is done in such way that the different available positions of the mobile structure control the phase shift along a certain transmission line of the circuit. The paper explains this mechanism and the implemented devices in depth; it describes its advantages and shows some examples of application.

KEYWORDS: Microwave heating, microwave parameters measurement, impedance matching, power delivery, microstrip instrumentation.

INTRODUCTION

The field of radio frequency (RF) and microwave engineering covers the behavior of alternating currents with frequencies ranging from 100 MHz to 1000 GHz. To be more concrete, radio frequency (RF) signals are considered as those with frequencies between 30 MHz and 3 GHz, and subdivided in Very High Frequency (VHF) for those covering the 30 MHz

- 300 MHz range and Ultra High Frequency (UHF) for those between 300 MHz to 3 GHz. Microwaves are often considered to range between 3 GHz to 300 GHz, and they owe their name to the short wavelengths corresponding to such frequencies ($\lambda=c/f$): from 10 cm to 10 mm. Due to this short wavelengths, comparable to a common printed circuit board (PCB) dimensions, Kirchhoff Laws and standard circuit theory in general are no longer applicable to solve circuit problems in the microwave band. Standard circuit theory is, in that sense, a particular case of Maxwell Equations applied to circuits excited by low frequency signals. In a microwave problem, the elements of a circuit usually act as *distributed elements*: the phase of the electromagnetic wave varies significantly along its longitude, and connectors, discontinuities or adjacent materials induce changes on the propagation characteristics of the wave.

According to that stated before, it could be said that a microwave circuit is integrated not only by the electric circuit itself, but also for all the conductive or dielectric elements in the PCB or near it. Every structure connected or near a microwave circuit interacts with it and affects its performance, so the variability of any Radio Frequency (RF) or microwave circuit parameter becomes much more problematic than the corresponding low frequency problem. The inclusion of mechanical structures which may interact in a certain way with the performance of the circuit suppose the introduction of non-desired effects and a powerful degradation of its response. For example, in the case of a conventional power divider implemented by using $\lambda/4$ transmission lines, it is needed a certain impedance relation between the lines that it includes for the device to perform as a divider. The characteristic impedance and length of those lines compared with the ones from the main transmission line must be of such value that the equivalent impedance seen from the divider input is the correct one. If this relation does not apply, then an impedance mismatch occurs and, consequently, reflections are produced in the divider input, along with disequilibrium in the power delivered to each one of the output ports.

Special efforts might be invested in the characterization of these unwanted interactions for a design like those presented in this paper to be successful. Continuing with the $\lambda/4$ divider analogy, it is not trivial to be able to vary the characteristic impedance of each line of the circuit independently. Usually, any variation of the boundary conditions applied to the circuit could vary its features as a whole, and not to be as selective as needed with the transmission lines which it affects. For that reason, adjustable microwave and RF circuits are usually implemented using semiconductor switches or control components which may respond to a certain DC stimulus by allowing binary selections of different electric circuits. This way, it is possible to implement phase shifters or variable reactances with a finite number of possible values. This offers predictable, repetitive and electronically controlled microwave responses for a circuit. Nevertheless, the use of these methods increases its complexity both in design and control with the need of more and in more possible selection values.

Some examples of control devices are those implemented using active components such as diodes acting as switches for selecting different output ways for an input signal. A simple digital phase shifter can be designed using diodes just like the one presented on the Figure 1. The diodes array conform a SPDT switch, in which the different output ports can be selected depending on the polarization of each one of the diodes. Then, each port of the SPDT switch is connected to a transmission line of a certain length, as the case of Figure 1, or different reactive networks which may shift the phase of the transmitting wave in a different way. Those reactive networks could be designed either

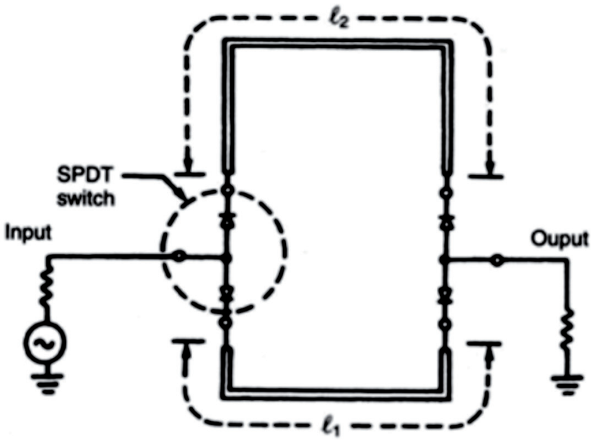

Figure 1. Example of a digital phase shifter.

using distributed elements as reactances or using lumped elements as RF capacitors and loops. This way, different electrical longitudes can be selected from a discrete set of them. Regardless of the method used to provide phase differences between the selector's outputs, which may be more or less problematic depending on the frequency, this kind of phase shifters are always limited by the total amount of phase differences they can present.

Another technologic solution for the particular example of phase shifting is the one implemented using radio over fiber technology. This technology takes profit of the features of light propagation over optical fiber. This way is possible to generate extremely pure RF and microwave signals, distribute them with minimum losses, antenna remote feeding, controllable phase shifting for antenna phased arrays and many other applications. Depending on their configuration, these systems can offer extremely high bandwidths and high reliability. They can also be set up to present a gradual phase shift with the variation of a certain circuit optical parameter, such as laser wavelength or fiber dispersion [Martí and Campany, 2009]. Such is the case of the configuration shown in Figure 2 [Coward, 1993; Esman, 1993]. Nevertheless these solutions are expensive and often unsuitable for a microwave laboratory, as they require of lasers, photodetectors and other expensive devices.

Variable matching networks and power dividers or attenuators can be implemented by using waveguide technology [Gerling, 2010], as the introduction of variable inductive or capacitive elements in the waveguide is much easier than the same task in planar devices. It can be done by introducing tubs or metallic elements. Nevertheless, in applications in which waveguide transmission is not the preference, and planar designs and cables are used instead, the use of waveguides with the only purpose of introduce variability can suppose an important raise in costs, weight and size, and it forces to introduce cable to waveguide transitions and other elements.

To solve these problems and being able to vary microwave circuits with the best possible resolution and improve power handling capabilities, the devices described in this paper are presented. These devices are capable of altering the physical (and therefore electrical) longitude of a microstrip transmission line mechanically, so the limiting factor for the adjustment resolution is not the number of active devices or different electric circuits anymore. The limiting factor becomes the mechanism used for moving the devices, either by hand or using motors. If controlled using electric motors for their adjustment, then the minimum spatial resolution of the motor would fix the available possible lengths of the transmission line. Regarding power handling, without any doubt these novel devices are capable to tolerate much higher power than other component-based designs, as they include only transmission lines. Maximum power will then be fixed by the maximum power that the conventional microstrip line is able to handle. This maximum power depends on the maximum temperature the elements of the circuit need to lose their properties or melt. This temperature is in turn conditioned by the dielectric losses, conductor losses, specific heat and mass of materials and the heat sink ability of the whole structure.

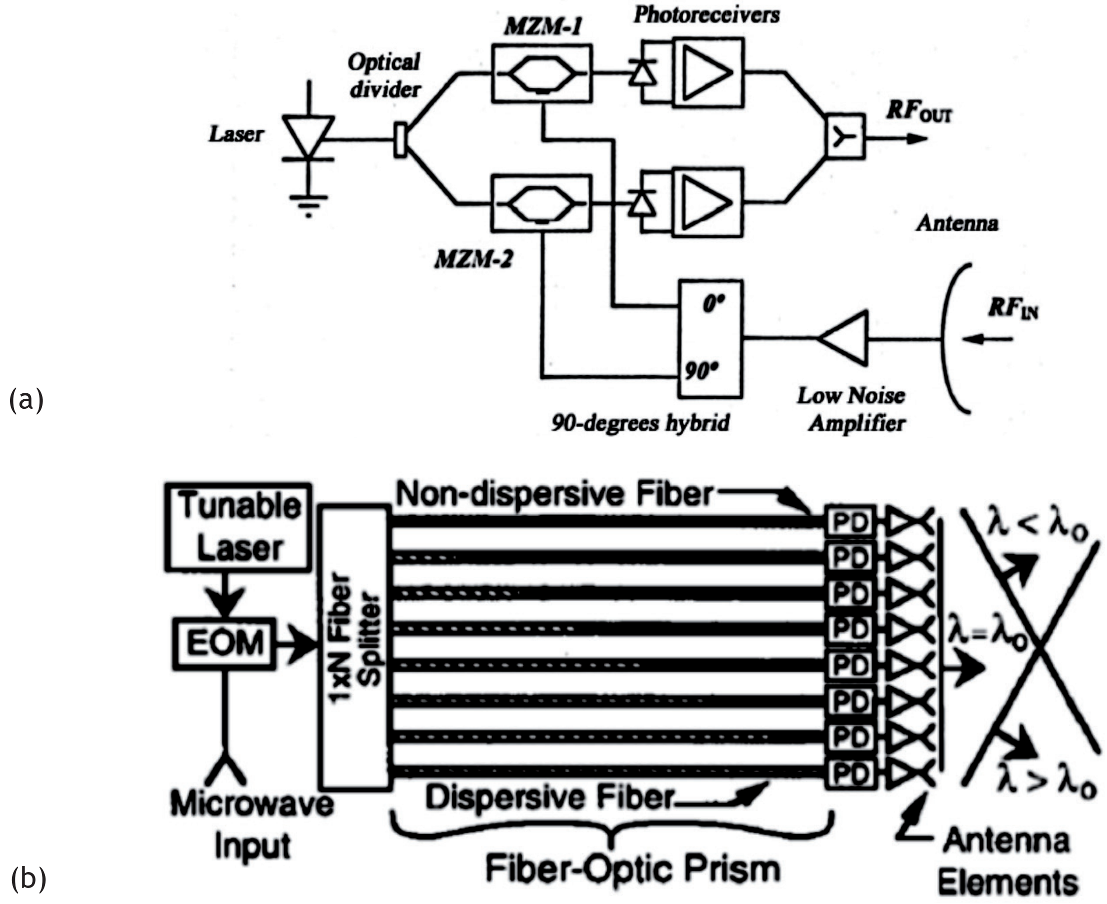

Figure 2. Example of an optical configuration for gradual phase shifting (a) [Coward, 1993] and another configuration used to feed a phased array antenna in which antenna main lobe can be controlled by an unique parameter: the tuneable laser wavelength (b) [Esman, 1993].

Ultimately, dielectric strength is the factor which determines the maximum electric field strength applicable to the used dielectric for it to not allow a discharge. However, this situation often happens at higher power levels than the failure caused by the heating by Joule effect if dielectrics are thick enough and heat sink is inefficient. The designs presented in this paper were first designed as low power prototypes in FR4 substrate and some of them were later updated to an improved version capable of higher power handling.

The development of this technology took place in the frame of a degree project on energetic applications of microwaves for Microbiotech SL (MBT). Microbiotech SL (MBT, in advance) is a knowledge-based company: its activity is the development of new technologic solutions based on the energetic applications of microwaves for many different fields such as industrial applications, medical applications or energy efficiency.

This devices response to the needs that the degree project came up against, such as matching impedance for the maximum transfer of microwave power between a microwave applicator and a compound of a sample of a confidential material provided by MBT. The electric parameters of the material sample were uncertain for us so impedance matching was needed, and so it was to deliver gradual amounts of microwave power to study different thermodynamic situations. All designs in this paper were made for the 2.45 GHz ISM band.

MATERIALS AND METHODS

The first stage prototype circuits presented in this paper were first simulated using a circuital model simulator: *AWR Microwave Office 2009*, and then produced by photolithographic methods. Substrate used for microstrip was FR4 kind, with the following specifications: $\varepsilon_r = 4.3$, $tan\delta = 24 \times 10^{-3}$, $t = 35$ µm, $h = 1.6$. Mechanical structures for the sliding mechanism were made of methacrylate by milling two different and complementary pieces.

The improved high power device presented in this paper was designed and simulated using the electromagnetic simulator *Ansoft High Frequency Structure Simulator* (*HFSS*), using Teflon as substrate with the following specifications: $\varepsilon_r = 2.1$, $\tan\delta = 10^{-4}$, $h = 3$ mm. The used technology was not a microstrip technology as usual, since microstrip line was introduced in the medium and not simply above it. Copper to conform the microstrip line was manufactured by milling a single sheet of copper with a 1 mm thickness. This line was then integrated in the Teflon substrate by milling its same shape and thickness in one of the surfaces of the Teflon and then introducing the copper line, (details are given in the high power design section below). Ground plane was made connecting a thick sheet of brass in the opposite face of the Teflon substrate.

Measurements shown in *measured results* section were taken using an Agilent/HP E5062A network analyzer in transmission or reflection configuration depending on the case. The final configuration is pointed out in each result. The calibration used was S.O.L.T. calibration (Short, Open, Load, Thru) using a Rhode & Schwarz R&S®ZV-Z129 calibration kit.

The mechanical sweep of the devices was manual for all the possible degrees of freedom of each one of them. Although this could introduce a certain measurement error, it was made in such way that it was minimized.

RESULTS

The resulting designs from a first development stage are shown in independent sections. Every section describes the electromagnetic fundamentals behind the design of each device, while measured results of manufactured prototypes are shown later in this results section.

Adjustable microwave power divider

The variable microwave power divider was designed in order to be able to represent different heating curves according to the delivered microwave power to the MBT sample, and given that our power source was not variable. The design was based on a waveguide design including two 90-degree hybrids connected in cascade [Gerling, 2010]. The variability of the structure is given by the difference of the electrical longitude between the two transmission lines which connect both hybrids, as shown in Figure 3.

This design takes advantage of the constant phase shift that the hybrids introduce in their crossed ports ($<S_{41}$) to generate an interference situation which might be either constructive or destructive according to the phase difference between ports 1 and 2 of the second hybrid in the schematic shown in Figure 1. This phase difference is directly proportional to the difference between the physical lengths of the two transmission lines uniting the 90-degrees hybrids, pointed out as Δl in the scheme shown in Figure 3. This sets out two limit situations: the first, when the phase difference of 90 degrees introduced by the first hybrid is maintained or switched to 270 degrees ($\Delta l = n\,\lambda/2$, with

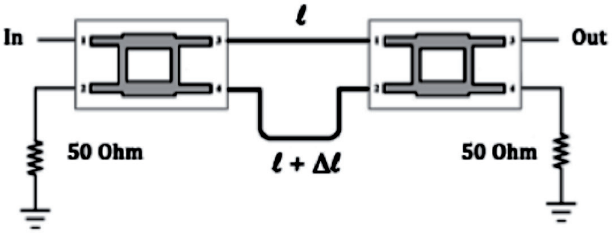

Figure 3. Schematic of the variable power divider.

n = 0, 1, 2 …), which would guide all the input power to port 4; and the second, when the phase difference is switched to 180 or 360 degrees ($\Delta l = n\ \lambda/4$, with n = 1, 3 ,5 …), which would direct the input power to port 3.

The mechanism is able to vary the electrical longitude of the microstrip transmission lines. As mentioned before, is based on the slide of a pair of parallel conductors united by a loop over another pair of fixed open-ended lines, as shown in Figure 4. This way, a variable longitude microstrip line can be synthetized, whenever ensuring the electrical continuity by the appropriate pressure of both boards. The mechanical pieces supporting the slide were made of methacrylate.

The election of the longitudes taking part in this mechanism is not trivial and requires of the study of some factors. The superior line uniting both hybrids must be long enough to ensure a minimum gap between the parallel lines, so couplings are avoided. In the other hand, this superior line should be as short as possible to minimize propagation losses. For that reason, this length is fixed to 20 mm before start calculating the rest of dimensions of the phase shifter: the rest of the degrees of freedom of the structure should be used for achieving the desired phase relations instead. Additionally, due to the topology it is impossible to reach a phase difference of 0 degrees: it is not possible for the inferior line to have an equivalent longitude equal to the superior line one. Because of that, this phase shifter will act from 180 to 360 degrees.

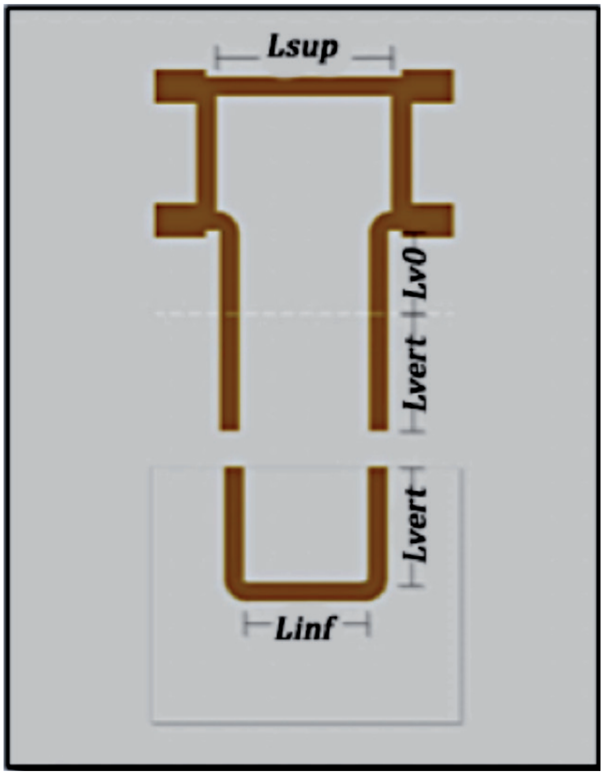

Figure 4. Scheme of the variable lines, specifying all their degrees of freedom.

Variable transmission line includes the four 90-degrees curved bends and the inferior horizontal line which can be seen in Figure 4. These elements are needed to conform the desired topology and they affect the total electrical length of the variable line, although its longitude is not variable. The only variable lines are the vertical lines on the design.

The ideal performance of this circuit requires the mobile conductors to be printed over air substrate ($\varepsilon_r \approx 1$). This would emulate the conditions present in any microstrip circuit, in which the conductors are actually covered by air on one of their faces. Even though it could alter the performance of the circuit, Neltec NY9220ST1143 ($\varepsilon_r \approx 2.2$) was used instead. To conclude, the vertical parallel lines must be a quarter of the guided wavelength.

Before the implementation of the final power divider, an insulated phase shifter was made, as well as an insulated 90-degree hybrid. This previous design stage was specially useful to determine the source of potential errors. Parameters elected were $w = 1.76$ mm, $L_{sup} = 20$ mm, $L_{inf} = 12$ mm, $L_{vert} = 17$ mm and manufactured circuit is shown in Figure 5.

Once seen that the isolated elements integrating the final divider perform as expected, the design of this final circuit is composed. Some dimensions of the integrated phase shifter had to be recalculated for its use in FR4 substrate and to improve

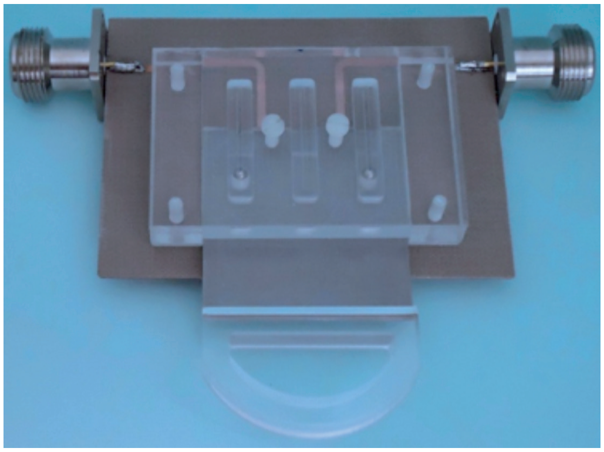

Figure 5. Phase shifter device.

the limitations seen on the isolated phase shifter response. This dimensions were w = 3.11 mm, L_{sup} = 28 mm, L_{inf} = 20 mm, L_{vert} = 19 mm. The final circuit is shown in Figure 6.

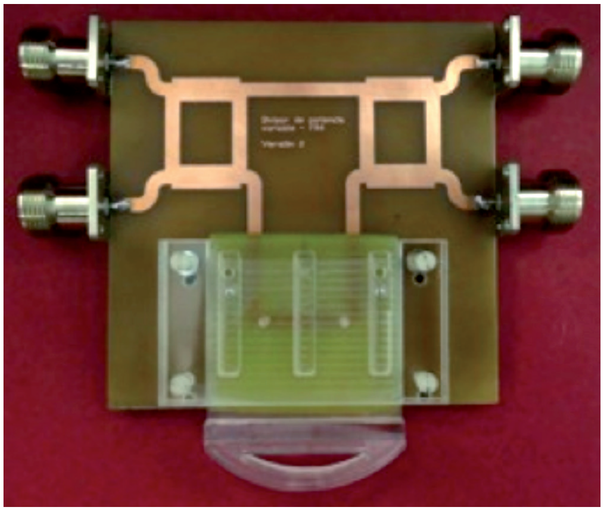

Figure 6. Adjustable microwave power divider.

Adjustable matching networks

As mentioned before, a variable impedance matching network was essential to deliver microwave energy to some samples of uncertain dielectric characteristics provided by MBT. This kind of samples could potentially mismatch the applicator used for this purpose. In addition, heat-insulating materials used for some measurements would mismatch impedance too, so a variable matching network as the one presented was essential.

As it is well-known from the basic microwave theory, when an electromagnetic mode is propagating through a transmission line of a certain characteristic impedance Z_0 and the transmission line is terminated with a load of an arbitrary impedance Z_L, as it could be an applicator, the needed condition for total power delivery is the impedance matching of the transmission line and the terminal load. If this condition does not apply, then a reflection occurs at the load's reference plane. This circumstance reduces the amount of power delivered to the load. Applying this principle to the particular case under study in this paper, the reader should note that the same situation occurs for a matched applicator when certain materials are introduced inside it. The presence of this material can modify the impedance of the applicator according to the relative permittivity of the sample and therefore reduce the amount of microwave energy delivered by the applicator to the medium. When the dielectric properties of the sample are uncertain or vary too much from one sample to another, then a fixed stub adaptor cannot fit all the needed situations. This is the reason why a variable impedance matching network was basic for the project. The impedance matching of the applicator for the new conditions of the medium can serve as a good practice to simulate any kind of mismatched impedance.

Impedance matching using an open-terminated stub printed a certain distance away from mismatched impedance has been widely studied and documented [Pozar, 2012]. It is one of the most basic and simple methods for impedance matching. The aim of the variable transmission line is to bring the load admittance to the intersection with the $g = 1$ circumference, in which real part of normalized admittance is equal to 1. Once done, the stub introduces a parallel admittance with the sign and magnitude able to compensate the reactance seen from the stub to the variable transmission line, and finally matching impedance for a narrow band. This is the process the designed device is based on.

The designed device allows the user to vary the stub length for a fixed width, this way being able to synthesize any reactance value and compensates it in the proper reference plane. The reference plane in which the stub is introduced is controlled by a phase shifter like the one designed for the previous power divider. According to this implementation, this impedance matching network or tuner has two variables.

Although it was not manufactured for this project, a three variable tuner can be implemented using this technology by printing three variable-length stubs, like the one used for the two variable tuner, spaced an odd multiple of a quarter wavelength between them.

The variable transmission line included in this two variable tuner is the same as that designed for the variable power divider described before, which would ensure the minimum 180 degrees phase shift. The open stub was elected to have an available sweep of a half wavelength in the guided medium, 34 mm, so it could synthetize any reactance. The final circuit can be seen on Figure 7.

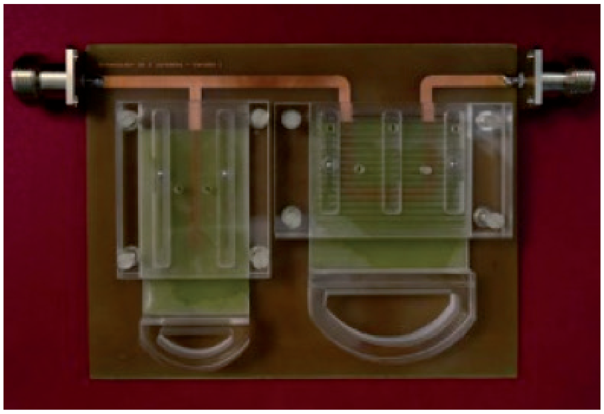

Figure 7. Adjustable matching network.

High power designs

As explained in the introduction of the present paper, an improved high power device was designed in planar technology. This device was decided to be a variable two-stub tuner, and it bases its variability in the same mechanism that the previous designs: two milled pieces of methacrylate, which support the slide of another mobile board whose conductor is always kept in contact with the conductor on the main board. The main difference between this design and the previous ones is the transmission line used to propagate the electromagnetic wave. In this case, it is not a conventional microstrip line: its main copper conductor is not much thicker than the substrate height, and this copper is not fixed above the upper surface of the substrate as usual. The substrate is milled following the shape of the main conductor as shown in Figure 8, so it can be surrounded by the material with the exception of its upper face. For those reasons electromagnetic simulation was elected to calculate the characteristic impedance of this kind of transmission line instead of circuital simulators or approximated equations, as they do not include circuital models or approximations close enough to the real electromagnetic problem.

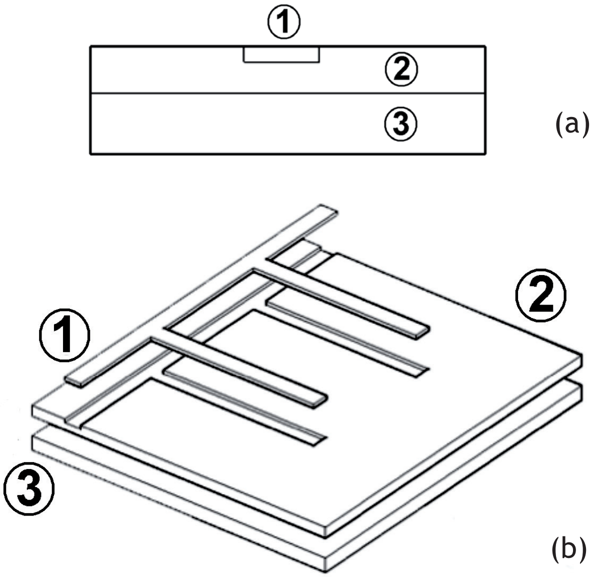

Figure 8. Scheme showing the high power transmission line (a) and the two-stub tuner design implemented using this technology (b). The different materials are pointed out in the pictures, namely 1 mm copper (1), 3 mm milled Teflon™ with ε_r=2.1 (2) and 4 mm brass (3).

The high power matching network was implemented using a two-stub configuration with a fixed distance of $3\lambda/8$ between them. The two-stub tuner configuration is not less documented than the one-stub matching network: it is a common technique, and it introduces the advantage of having a fixed electric length both between stubs and to the load. This way, the variable length transmission lines in the design are only responsible for the reactance of the two parallel stubs, but they do not support the propagation of the electromagnetic wave. The electrical length experienced by the propagating wave is therefore independent of the tuning mechanism unlike the case of the matching network previously presented, and so insertion loss in matching circumstances. The materials selected for this configuration were a copper thick sheet (t = 1 mm), so losses regarding conductors are minimized as resistance per length unit decreases; a dielectric substrate with a very low loss tangent at the frequency of interest ($tan\delta \cong 10^{-4}$) and thick enough to avoid dielectric breakdown (h = 3 mm) and to be massive enough to improve its thermal features; and, finally, a ground plane and heat sink made of brass. The thermal design of the brass ground plane is not addressed in this paper, but it could possibly be a decisive factor in the power handling capability of the device.

Simulations show insertion losses as small as 0.03 dB and reflection coefficients smaller than -40 dB for the design frequency 2.45 GHz. For the conductor and substrate thicknesses and electrical features described before (t=1 mm, ε_r=2.1, h=3 mm, $tan\delta \cong 10^{-4}$), the main's conductor width of the 50 Ω characteristic impedance planar transmission line like the one shown in the scheme in Figure 8 is W_m = 4.94 mm.

Measured results

Results of the mechanical microstrip phase shifter can be observed in Figure 9 and Table I. The Smith Chart showing the transmission response of the phase shifter, both simulated and measured from prototype. Distance from the center of the chart reflects the transmission coefficient and angle from horizontal shows phase shift.

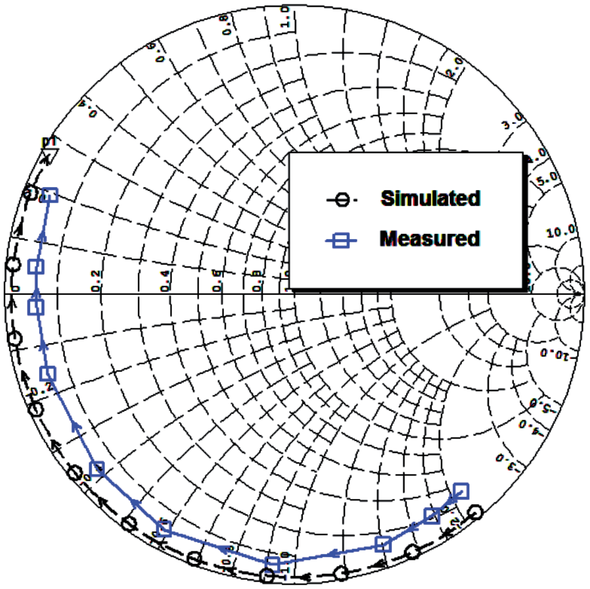

Figure 9. Transmission response simulated using Microwave Office and measured from prototype. Sweep cover slide from 0 to 17 mm at 2.45 GHz.

Table I. Comparative results of simulated and measured response of the phase shifter at 2.45 GHz. Mean of the insertion loss for different slide longitudes is taken to reduce the dependence of the final error with the one made by manual sweeping of slides.

	Phase shift	Insertion Loss
Measured (Deviation from simulation)	143.24°(-14.89°)	0.8 dB (+0.599 dB)

Phase shift deviation is due to imprecisions in the methacrylate sliding mechanism, which may not sweep along the desired length but along some millimetres less, and due to changes on propagation properties of the microwaves through the mobile board, as it is not made of air. In the section of the transmission line in which both the fixed and the mobile boards coincide, boundary conditions are not the same that in the rest of the microstrip transmission line. The main conductor is not covered by air: it is, in turn, covered by a multilayer substrate including the mobile board substrate and air. This circumstance changes the effective dielectric constant of the transmission line in those sections, and therefore the guided wavelength so the same physical longitude would correspond to less phase shift. Similarly, electrical discontinuity between the conductors of both boards and connectors contribution are not considered in the simulation model. This may led to the error regarding insertion loss.

Results of the final power divider are shown in Figure 10 and Table II. Measured results fit reasonably the expected ones, therefore validating the design. Output ports show complementary responses along the slide longitude sweep. However, optimizing the degrees of freedom of the phase shifter and using a better quality substrate could achieve better performance. These improvements are taken into account for the high power devices presented.

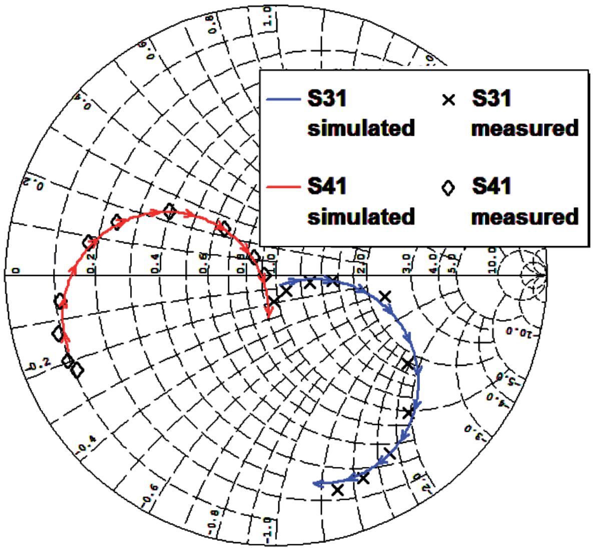

Figure 10. Transmission response simulated using Microwave Office and measured from prototype. Sweep cover slide from 19 to 38 mm at 2.45 GHz.

Table II. Results of measured response of the output ports of adjustable divider. Variations from simulated circuit are shown between brackets.		
	Directivity	Insertion Loss
Port 3	21.66 *dB* (+4.57 *dB*)	1.61 *dB* (-0.178 *dB*)
Port 4	26.126 *dB* (-2.05 *dB*)	1.674 *dB* (-0.263 *dB*)

In regard to variable matching network, simulated and measured results are shown on Figure 11. As it can be seen, measured response fits near perfectly the simulated ones. Minimum insertion loss and reflection, which correspond to transmission to a matched load, are 1.6 *dB* and -26.41 *dB* respectively.

As an example of use of the variable matching network for the case of a material introduced in an applicator and mismatching it, in Figure 12 it can be seen the reflection responses of the applicator in open space, mismatched with a MBT sample and finally matched using the presented device.

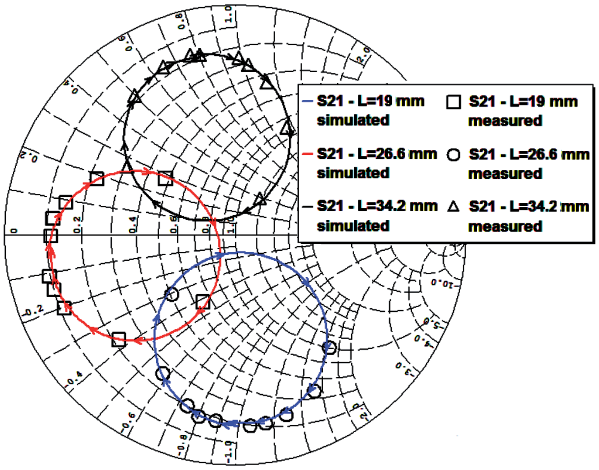

Figure 11. Transmission response simulated using Microwave Office and measured from prototype. Sweep covers stub longitude from 34 to 68 mm for 3 different phase shifts at 2.45 GHz.

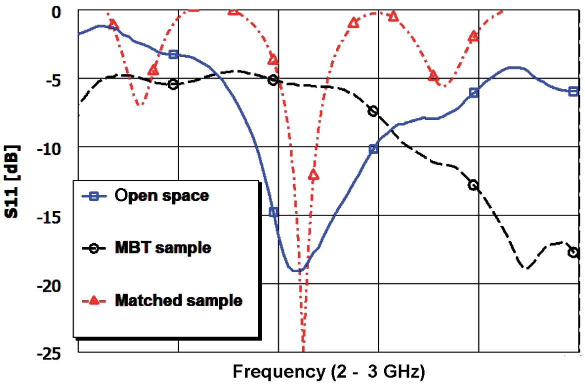

Figure 12. Reflection response of a microwave applicator in open space, mismatched with a MBT sample and matched using the presented device.

DISCUSSION

The obtained data of the implementation of the described devices show how their measured responses fit reasonably the simulated ones. Deviations are always explainable according to the physical features of the mechanism, and can be corrected generating better-conditioned simulation models as in the case of the high power matching network described before. For those reasons the implemented technology can be considered a feasible, predictable and repeatable technology.

The developed variable microstrip devices are useful to those applications in which a very sensitive adjust should be made. Laboratories and other research entities in which controlling the amount of energy delivered is a key factor would probably find this technology useful instead of the previously described technologies like diode switching-based phase shifters or photonic-based devices, which are usually more expensive. Some of the applications in which this technology can be useful is those related with controlled microwave heating, as the presented devices bring the ability to control the energy flow instantaneously and with very high resolution, even in those applications with higher power.

Medical applications such as hyperthermia microwave-based applications could find this technology quite useful. Human body tissues use to have a high, and variable, dielectric constant, so the introduction of any applicator in this kind of material powerfully mismatches the impedance, therefore generating very high VSWRs. This leads to inefficiency in the application and the excessive heating of transmission lines before the applicators. With the use of a high power impedance matching network as the one described before, microwave power transmission could be adjusted to be total, so the described problems are avoided, while the application system is still an easy to use, light-weighted and lossless system.

As a final application of these devices, its use in educational organizations can be pointed out. As they make use of basic fundaments of transmission lines and microwave theory, the presented devices could serve as graphical examples to reinforce the theoretical concepts. One-stub and two-stub tuning can be characterized for different stub longitudes and its effect can be immediately checked using the appropriate measurement devices such as network analyzers or spectrum analyzers.

CONCLUSION

The presented paper aimed to present the technology developed and justify its feasibility, as well as giving some examples of useful applications for variable microstrip lines. It is not the aim of this technology to replace the state of the art of control devices in microwave technology, but proposing an affordable and simple approach which may be of interest for certain applications. With this kind of devices it is possible to mechanically shift the phase of an input microwave source, to perform a variable power division or match impedance of barely any load. Nevertheless, more work should be done regarding optimization of the models and power tests. Insertion losses and response accuracy could be significantly improved using better quality dielectric materials for the microstrip circuits.

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