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UHF RFID Antennas for Printer-Encoders—Part 2: Antenna Types

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Understanding antenna performance is one key to obtaining accurate and reliable writing of RFID tags, especially in a high-volume automated system

Part 2 of this article continues the discussion of RFID antennas with a look at the operating environment. of antenna and its associated RFID tag printer-encoder. Readers may wish to have Part 1 available to follow the author's references to earlier comments and figures.

3. UHF Printer-Encoder Environment

Smart Label design restricted by the antenna-transponder interaction in very close proximity is complicated further by the Printer-Encoder environment. A common architecture of a thermal transfer UHF RFID Printer-Encoder (Fig. 5) yields an arrangement of four key internal areas: the *media supply zone,* the *following adjacent transponders zone,* the *targeted transponder zone* and the *encoded transponder zone.* This representation assumes that the antenna is positioned underneath the printhead and behind the platen roller. During printer operation, the transponders pass through the zones sequentially from the media roll to the printhead. Each zone can be active or inactive in terms of its ability to activate the transponders located in it. The zone lengths are correlated to the printer structure, the antenna construction and its dimensions. Consequently the zones impact the Smart Label design and impose constraints on the minimum Smart Label *pitch* and on the two transponder placement parameters: the *placement starting distance* and the *transponder placement range* (Fig. 1).

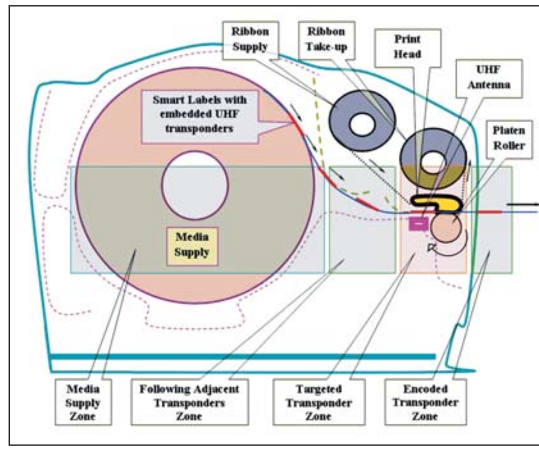

Figure 5 · Common architecture of thermal transfer UHF RFID Printer-Encoder.

Media supply zone usually has a fixed length. This zone is relatively far away from the antenna and is inactive. In case of parasitic activation of the transponders in this zone, the simplest solution regardless of the antenna and label dimensions is shielding.

Following adjacent transponders zone has a variable length. Typically the design goal is to make this inactive zone as long as possible in order to be able to process densely spaced short labels and achieve a short pitch. If an antenna positioned right after the platen roller has intensive radiation or an extensive longitudinal length, the inactive *following adjacent transponders zone* shrinks. In this case the printer can still process narrow labels but with an extended *transponder placement range.* The printer requires an increased *pitch* on the liner (Fig. 1(b)). This approach leads to a noticeable waste of liner material and limits the minimum label length. In order to protect the transponders against activation in this zone shielding component may be used. The disadvantage of a shielding solution is that the geometries of the shielding components depend on the transponder dimensions and involve adjustment for every new transponder formfactor.

Targeted transponder zone generally depends on the antenna and the transponder dimensions as well as the Reader's RF power. This zone is active, of course. When the antenna occupies much of the space between the platen roller and the media supply roll, the *targeted transponder zone* is relatively long. An extended *targeted transponder zone* requires either a long label or an outsized pitch in order to avoid collisions or transponder re-encoding with the wrong data. A short antenna, closely positioned to the platen roller, affords a short *placement starting distance* for the transponders and their short *transponder placement range.*

Relatively short labels often have a partition distance between them that is only a fraction of their width (Fig. 1(d)). Consequently, transponders embedded into such labels are grouped close to each other. In this dense arrangement all transponders can be activated simultaneously by a "low" resolution antenna. The long range RFID systems commonly employ an anti-collision technique for processing a group of transponders. This technique is impractical for Printer-Encoders because it is unable to identify single targeted transponder. Only an antenna with spatial selectivity can work with a single closest transponder without activating the adjacent ones. The higher the spatial selectivity of an antenna, the shorter the *transponder placement range.* In the best case the *transponder placement range* can equal the transponder's width. The shielding components can also be used to form the *targeted transponder zone* or to limit its longitudinal length with the same disadvantages as for the *following adjacent transponders zone* application described above.

Encoded transponder zone length mainly depends on the antenna field strength and the printer components surrounding this area. The *encoded transponder zone* should be inactive. The antennas with highly intensive electro-magnetic field and some printer components with the wave re-radiating ability can inadvertently make this zone active. In this case every encoded and printed label must be either peeled or torn off in order to prevent the transponders collision or an incorrect re-encoding. The need to take off the encoded transponders prohibits printer operation in the batch processing mode. Alternatively the label pitch may be increased such that the encoded transponder leaves this zone when the next transponder arrives for an encoding. The application of the shielding components suppressing electro-magnetic field in the *encoded transponder zone* imposes functional limitations on the printer. For example, the shielding elements mounted in this zone conflict with the use of an external cutter.

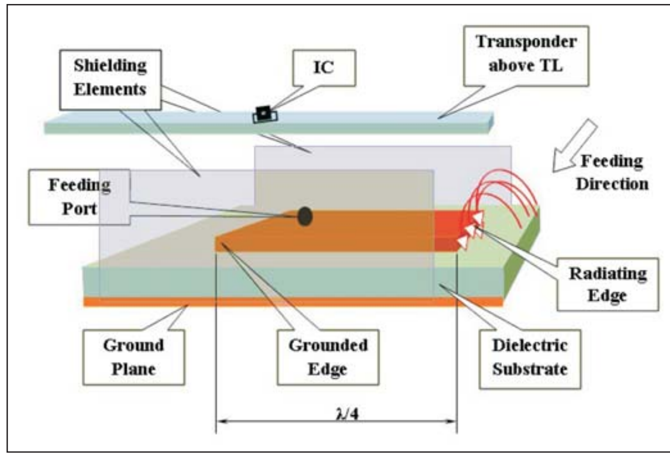

Figure 6 · Open Transmission Line antenna—λ/4 wavelength microstrip patch.

Two criteria are proposed for the integral characterization of relations between the antennas construction, the printer zone dimensions and the Smart Label design parameters. The first criterion is the *antenna structural feasibility,* which reflects the space required for the antenna installation and designates the interval occupied by the antenna along a transponder's path. The second criterion is the *transponder placement boundaries,* which characterizes the antenna spatial selectivity and the associated transponder placement parameters of the Smart Label.

These four criteria established above are intended to be utilized for the comprehensive study and comparison of the existing UHF antennas for stationary and mobile RFID Printer-Encoders and also to determine the correlation between the printer encoding function and the Smart Label parameters limitations.

4. UHF Antennas for Stationary Printer-Encoders

Microstrip, stripline and others PCB transmission lines developed primarily for RF energy transfer have become accepted as antennas by UHF Printer-Encoders and by other RFID close proximity applications. Their planar structure, ability to handle relatively high RF power and inexpensive, precise fabrication process enable easy integration. Any transmission line antenna significantly changes its behavior and electrical properties depending on the line length and its terminating status. There are two TL antenna types: *Open TL* type based on the open TL and *Terminated TL* type—antennas based on the loaded TL.

Antenna Based on Open TL

An Open TL antenna type is represented by a quarter-wavelength microstrip patch antenna (Fig. 6) [21], [22]. The patch antenna for close proximity applications differs from a conventional patch antenna in having shielding components along the non-radiating patch sides and a much narrower radiating edge in order to decrease field strength in radiating near- and far-field zones.

Antenna Structural Feasibility

This antenna is based on PCB and enclosed in shielding case with one open side. The antenna is arranged in parallel with a transponder in an encoding area and resides in interval of 20-25 mm (including its mounting components) behind the platen roller.

Transponder Placement Boundaries

The antenna is positioned close to the platen roller and provides a short *transponder placement range* and *placement starting distance,* which allows the processing of short Smart Labels with a short pitch.

The antenna shielding elements are engaged to limit the transponder interrogation interval. Electro-magnetic shielding is probably the oldest method of insulating the transponder designated encoding area. In RFID technology shielding was initially employed for selective single transponder testing in the presence of others [23]. The shielding disadvantage appears when transponder form-factors change frequently, for example, for different label sizes, and so do the geometries of the shielding elements.

Encoding Field Intensity

Parallel alignment of the antenna with a transponder in the encoding area ensures improved coupling. However, because electrical charges are highly accelerated at the open edge of the antenna, it has very strong reactive and radiating near-field intensity. The antenna energy efficiency is very high and a transponder encoding at 5-10 mm from the antenna requires a few milliwatts of the Reader RF power. Shielding elements create losses in the antenna near-field and change its distribution around the antenna. Shielding reduces energy in the area of adjacent transponders but works inefficiently for radiating near- field. A strong antenna electric field can potentially activate the transponders in *encoded transponder zone* or in *following adjacent transponders zone* (Fig. 5) and thus this antenna requires RF power control to reduce this field. The collision risk drives the Reader operational RF power down to the level that is insufficient to activate transponders in the adjacent zones and significantly decreases system power margin as illustrated by Antenna #1 in Figure 3. Magnetic field mostly concentrated near the grounded edge partly contributes to the transponder activating power.

Impedance Bandwidth

Antenna feeding port impedance match is achieved by finding the appropriate point close to the grounded edge of the patch (Fig. 6). Bandwidth of patch antennas without a shield is narrow, approximately 30 to 50 MHz. In order to tolerate parameter deviations the geometry of every antenna must be adjusted for frequency tuning and impedance matching.

Antennas Based on Terminated TL

In contrast to Open TL, antennas based on Terminated TL could be resonant or not-resonant. They may have wide or narrow bandwidths depending on the TL length and the terminating load value. In the most common case a terminated TL exhibits three specific features that have defined three trends in UHF antenna development for very close proximity RFID applications. These features are related to the TL input impedance.

The input impedance Z_{IN} of any loss-free TL having characteristic impedance Z_C, a length l and terminated by a load Z_L in general is described [24] as

$$Z_{IN} = Z_C \left(\frac{Z_L + jZ_C \tan \beta \ell}{Z_C + jZ_L \tan \beta \ell} \right) \tag{4}$$

where β is the phase constant, which for a uniform, loss-free TL is inversely proportional to a wavelength λ and is given by

$$\beta = \frac{2\pi}{\lambda} \tag{5}$$

Substituting (5) in (4) we obtain:

$$Z_{IN} = Z_C \left(\frac{Z_L + jZ_C \tan \frac{2\pi}{\lambda} \ell}{Z_C + jZ_L \tan \frac{2\pi}{\lambda} \ell} \right) \tag{6}$$

There are three conclusions of interest from equation (6).

1. If TL characteristic impedance Z_C meets the condition:

   $$Z_C = Z_L \tag{7}$$

   Then substitution of (7) in equation (6) gives:

   $$Z_{IN} = Z_L \tag{8}$$

   In reference to (8) the impedance Z_{IN} is theoretically independent of TL length and equal to the terminating load for any frequency. Although in reality the bandwidth is limited by parasitic effects associated with non-ideal TL components, it can easily reach 5 to 6 GHz. In this case voltage standing wave ratio (VSWR) of the TL is about 1; voltage along the whole TL length is equal to the input voltage. The electric field strength distribution around the TL is also homogeneous.

2. If the TL length is a quarter-wavelength:

$$l = \lambda / 4 \tag{9}$$

Substituting $\beta l = \pi/2$, from (5) and (9) in (6) obtain:

$$Z_{IN}(f_0) = \frac{{Z_C}^2}{Z_L} \tag{10}$$

The ability of TL to transform load impedance (10) is widely used for impedance matching in the vicinity of one particular operational frequency (f_0).

3. If the TL length satisfies the condition:

$$l = \lambda / 2 \tag{11}$$

Substituting $\beta l = \pi$, from (5) and (11) in (6) obtain:

$$Z_{IN}(f_0) = Z_L \tag{12}$$

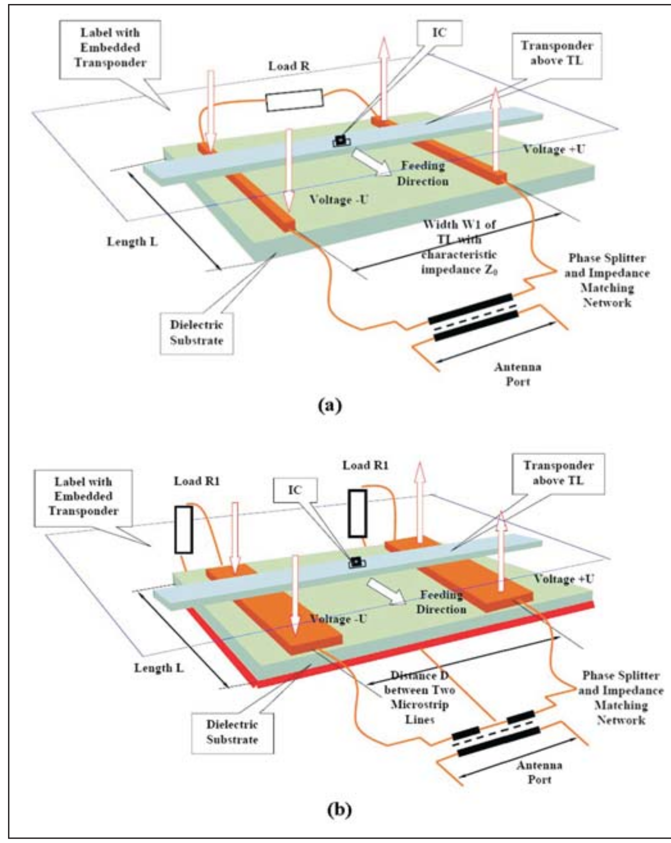

Figure 7 · Antennas based on Terminated Non-Resonant TL. (a) "Two-Wire" transmission line; (b) "Dual Microstrip" transmission line.

Equation (12) is valid for any impedance value Z_C for one particular frequency f_0. TL experiences a standing wave with SWR ≥ 1 depending on how much impedance Z_C differs from impedance Z_L. In an extreme case for a huge mismatch SWR >> 1, the voltage amplitudes near the edges of a λ/2 wavelength TL are in anti-phase and can attain almost a double the input voltage value. This voltage amplification increases the electric field strength immediately adjacent to the TL and for SWR >> 1 is almost equivalent to the input power increase of up to 4 times for the matched TL.

Antennas Based on Terminated Non-Resonant TL

The so-called Terminated Non-Resonant TL antennas are presented by "Two-Wire" TL [25] (Fig. 7(a)) formed by two PCB traces and by a combined arrangement of two microstrip transmission lines [26] (Fig. 7(b)). This group of antennas utilizes the TL phenomena (8). For all antennas based on terminated TL, their electrical charges slowly accelerate at the edges. Therefore, the antennas have a weak radiating near- and far-field intensity, while high current provides relatively strong reactive near-field.

Antenna Structural Feasibility

Both antennas, based on a highly technological PCB fabrication process, have an orthogonal alignment of their traces with the targeted transponder. Their structures take up to 45-60 mm in longitudinal length (including the mounting elements) from the platen roller back to the media roll. The antennas are very convenient for implementing a transponder interrogation method known as "encoding on the run" along the media feed direction. The distance between the "wires" on the dielectric substrate is 20-40 mm (Fig. 7(a)). The combined structure, "Dual Microstrip" transmission line, is 45-60 mm in length with two microstrips 20-40 mm apart (Fig. 7(b)).

Transponder Placement Boundaries

Both antennas have an excellent selectivity outside of the *targeted transponder zone* (Fig. 5) to prevent communications with adjacent transponders; however, the zone itself is much wider than a transponder width. Antennas must be field upgradeable for different transponder form-factors and redesigned to adjust the *transponder placement range* (Fig. 1(b)). With these antennas a long pitch is required to encode short Smart Labels.

Encoding Field Intensity

Depending on permittivity of the dielectric substrate, antennas can have a width of traces approximately 1.5-3 mm either for the "Two-Wire" TL or for the "Dual-

Microstrip" TL to attain characteristic impedance of 100 ohms. Because of the antenna-transponder orthogonal orientation, the antennas form a small mutual static capacitance and have a loose coupling with transponders. The areas of the electric field strength for the "Two-Wire" TL are not quite close to transponder's most sensitive edges. Both antennas have comparatively low power efficiency but could have a high RF power margin. The areas of intensive electric field of the "Dual-Microstrip" structure are positioned closer to the sensitive transponder edges but the mutual overlapping area is small and the coupling grade is still low. The electric field strength is homogeneous along both transmission lines and amplified by transformer usage. Magnetic field surrounding every TL is practically not contributing to transponders activation power.

Impedance Bandwidth

Both transmission lines are terminated by loads matching their characteristic impedances. They have SWR ~1 over a frequency band that is much wider than 1 GHz. The "Two-Wire" TL width W1 defines its characteristic impedance that is about 300 ohms. To satisfy the condition (7) TL is loaded by a 300 ohm resistor. An RF transformer with impedance ratio equal to 6 is used to provide the 50 ohm antenna port impedance match and anti-phase voltages. The combined structure—"Dual Microstrip" transmission line (Fig. 7(b)), loaded by two 100-ohm resistors R1, makes the characteristic impedance of the antenna independent of the distance *D*. It also uses an RF transformer with the impedance ratio of 2 for impedance matching and phase shifting.

Antennas Based on Terminated Uniform Resonant TL

The second type of antennas is based on terminated but mismatched TL. The so-called Terminated Uniform Resonant TL antennas are demonstrated by the λ/4 (Fig. 8(a)) and the λ/2 (Fig. 8(b)) length of the uniform microstrip TL. This group of antennas realizes TL phenomena (10) and (12) respectively. Antenna port impedance is matched to the system impedance without additional matching network.

Antenna Structural Feasibility

Both antennas are in parallel alignment with the targeted transponder and occupy a 20-30 mm interval behind the printer's platen roller.

Transponder Placement Boundaries

These antennas allow a printer to achieve a short transponder placement starting distance 10-15 mm and placement range 20-25 mm for transponders with dimensions 8 × 95 mm or 10 × 95 mm [11, 13]. The pitch for the labels is in the range of 40-50 mm.

Encoding Field Intensity

The microstrip TL base element for these antennas has a lower characteristic impedance Z_C than the load impedance Z_L and therefore a wider than non-resonant TL conductive strip, which increases static capacitance and a coupling with a transponder. The impedance mismatch causes a wave reflection with standing wave ratio SWR >1 along the line and increases the electric field strength above the line. The reflection coefficient Γ is a complex voltage (current) ratio, which may be expressed in terms of the antenna characteristic impedance and load impedance (Z_C and Z_L) correspondingly:

$$\Gamma = \frac{Z_L - Z_C}{Z_L + Z_C} \tag{13}$$

Substituting (13) in (3) we obtain

$$SWR = \frac{Z_L}{Z_C} \tag{14}$$

The equation (14) shows that an increase in ratio between the load impedance Z_L and the microstrip impedance Z_C causes an amplification of SWR and makes stronger electric field above the TL. The impedance Z_C is inversely proportional to the conductive strip width W2 or W3 (Fig. 8(a) and (b)). For both antennas the conductive strip widths can be made comparable to the transponder width and RF power margin can attain 3-6 dB level without a significant expansion of the encoding range.

The quarter-wave TL antenna contributes to transponder power delivery by electric field at one side of the TL and by magnetic field at the transponder's center. The half-wave TL antenna is twice as long, has double the mutual static capacitance with a transponder, and therefore maintains an enriched coupling and encoding field intensity.

Impedance Bandwidth

The geometries of λ/4 and λ/2 TL antennas, terminated by mismatched loads, define their resonant frequency and consequently their bandwidth. The bandwidth Δf of the quarter-wave TL antenna can be obtained from [27],

$$\Delta f = f_0 \left\{ 2 - \frac{4}{\pi} \arccos\left[\frac{\Gamma_m}{\sqrt{1-\Gamma_m^2}} * \frac{2\sqrt{Z_0 Z_L}}{|Z_L - Z_0|} \right] \right\} \tag{15}$$

Applying equations for microstrip characteristic impedance and strip width from [28], the bandwidth of the quarter-wave TL antenna is calculated using equation (15) for the frequency 915 MHz as a function of the strip width for impedance Z_L in the range of 2 to 8 ohms (Fig. 8(c)). The plot shows that the strip width W2 can be increased up to 35 mm without violating the justified antenna bandwidth of 150 MHz.

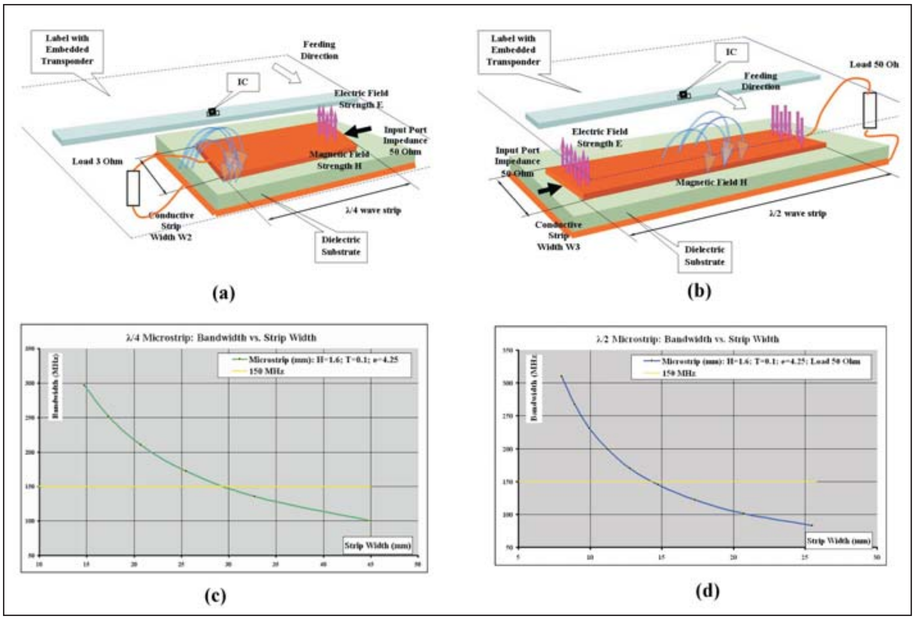

Figure 8 · Antennas based on Terminated Uniform Resonant microstrip TL for 915 MHz band. (a) λ/4 TL antenna; (b) λ/2 TL antenna; (c) λ/4 TL bandwidth vs. width; (d) λ/2 TL antenna bandwidth vs. width.

Substituting the antenna length $l = \lambda/2$ in (6) for port impedance Z_{IN}, for the half-wave TL antenna the reflection coefficient Γ is:

$$\Gamma = \sqrt{\frac{\left(Z_0^4 - Z_L^4\right)^2 \tan^4\theta + 4\left(Z_0 Z_L\right)^2\left(Z_0^2 - Z_L^2\right)^2 \tan^2\theta}{\left[4\left(Z_0 Z_L\right)^2 + \left(Z_0^2 + Z_L^2\right)^2 \tan^2\theta\right]}} \qquad (16)$$

where

$$\theta = \beta l;\ \theta = \pi \frac{f}{f_0}$$

For the maximum reflection coefficient $\Gamma_m = 0.333$ in (16) that corresponds to SWR = 2, θ_m and the bandwidth Δf can be obtained,

$$\Delta f = 2 f_0 \left(1 - \frac{\theta_m}{\pi}\right) \qquad (17)$$

where

$$\theta_m = \pi \frac{f_m}{f_0}$$

and f_m corresponds to Γ_m.

Using equations for microstrip characteristic impedance and strip width from [28], the bandwidth Δf from (17) of λ/2 wavelength TL antenna is plotted versus strip width W3 (Fig. 8(d)) for Z_L = 50 ohm and the frequency 915 MHz. In order to comply with the requirement of Δf = 150 MHz, the strip width W3 of the half-wavelength TL antenna should not exceed 14 mm. This bandwidth restriction limits the *transponder placement range* in the case when printer design requires a wide transponder encoding area.

Antennas Based on Terminated Tapered Resonant TL

Another sub-group of the second type of antennas is the so-called Terminated Tapered Resonant TL antennas. The design goal is to achieve for microstrip TL antennas a relatively wide bandwidth and an increased grade of coupling with transponders. This goal is accomplished by implementing a method previously developed for bandwidth enhancement of impedance matching TL transformers. This method is based on the theory of small reflections [24] applied to a tapered (non-linear) profile of characteristic impedance for any TL. Antennas are presented by the λ/4 wave and the λ/2 wave non-uniform microstrip TL.

Antenna Structural Feasibility

The width of the quarter-wave non-uniform microstrip TL is tapered from W4 to W5 (Fig. 9(a)). The edge widths of the half-wave non-uniform microstrip TL antenna are W6 (Fig. 9(b)). Both antennas can be made wider than the widths of uniform microstrip TL antennas. The corresponding lengths of non-uniform microstrip TL antennas are shorter than lengths of uniform ones because of the extension of the sides of the tapered microstrip TL. The considered example is the half-wave microstrip linear width (non-linear characteristic impedance) taper TL (Fig. 9(b)). The width of the TL varies linearly from 18 to 4.5 and back to 18 mm, the dielectric constant of the substrate is 4.25, and the height of the substrate and the length of the strip are 1.6 mm and 65 mm respectively.

Transponder Placement Boundaries

Terminated Tapered Resonant TL antennas can provide the same placement starting distance and placement range compared to the Terminated Uniform Resonant TL antennas with equally wide conductive strip. For an extended transponder placement range the tapered conductive strip can be made wider without sacrificing the antenna bandwidth.

Encoding Field Intensity

Field distribution above the quarter-wave terminated tapered TL antenna (Fig. 9(a)) covers only a part of the targeted transponder thus delivering half the power of the half-wave TL antenna. Electric and magnetic field distribution of the half-wave terminated tapered TL antenna (Fig. 9(b)) is concentrated at the most field sensitive transponder areas. The antenna with linearly variable width at the input end W6 = 18 mm maintains a greater mutual static capacitance with the transponder and provides a higher spatial selectivity than the uniform TL antenna with the narrower conductive strip. The RF power margin can achieve 6 dB without a significant increase in the transponder encoding range.

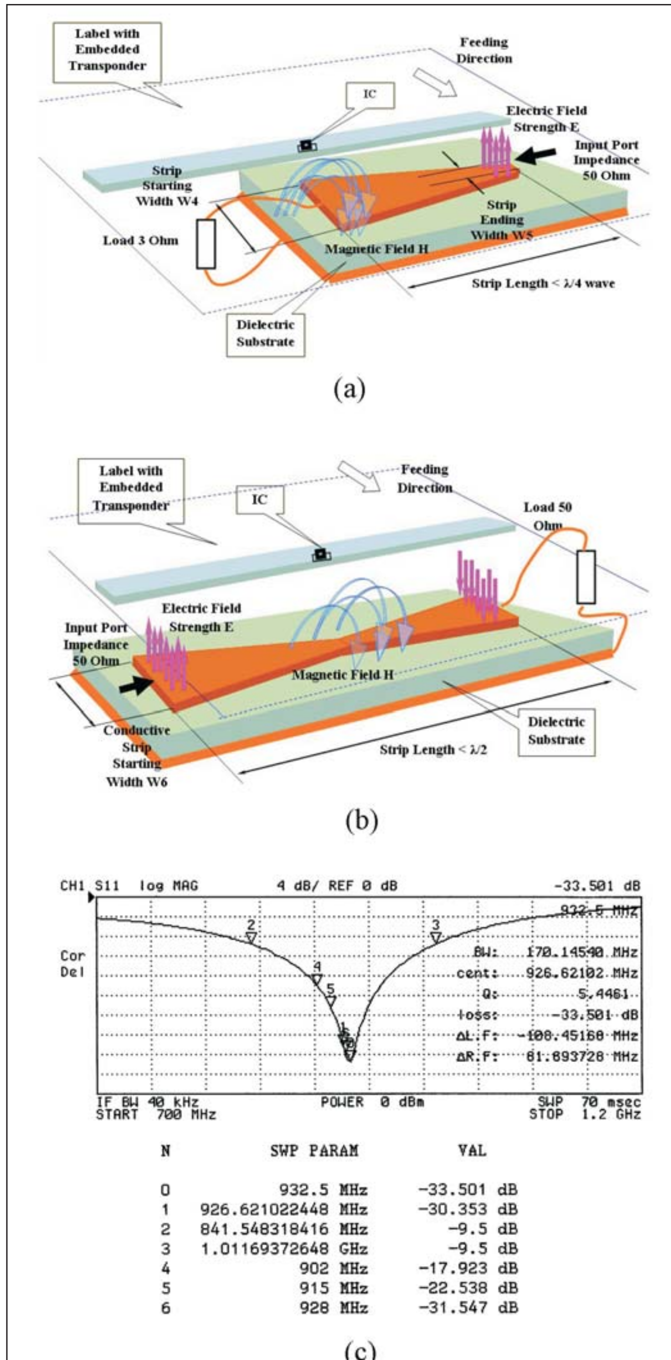

Figure 9 · Antennas based on Terminated Tapered Resonant microstrip TL: (a) λ/4 TL antenna; (b) λ/2 TL antenna; (c) S_{11} parameter for λ/2 TL antenna dimensions 4.5 × 18 × 65 mm.

Impedance Bandwidth

Like other terminated resonant TL antennas, the tapered TL antennas have their port impedance of 50 ohm without an additional matching network. In contrast to the uniform TL, the λ/2 wavelength linearly tapered width microstrip TL antenna has a widened bandwidth. Measured reflection loss (S_{11}) of an antenna with a conductive strip at the input end width W6 = 18 mm (Fig. 9 (c)) shows that its bandwidth exceeds 150 MHz. The taper implementation for the λ/4 wave microstrip TL is not necessary for the bandwidth enhancement unless dictated by other design reasons. The uniform λ/4 wave microstrip TL with a strip width W4 of up to 30 mm already has BW in the range of 150 MHz (Fig. 8(c)). The importance of tapered λ/4 wave TL sections was shown by Young [29, 30] for a bandpass filter design. He demonstrated that every second impedance step quarter-wave transformer replaced with an opposite impedance step provides the equal input and output impedances. It implies that the two parts of λ/4 wave tapered TL can be used as building blocks for tapered λ/2 wave TL antennas.

It was shown by Collin [24] that reflection coefficient of tapered TL is:

$$\Gamma_{IN}(f) = \frac{1}{2}\int_0^L e^{-2j\beta z} \frac{d}{dz} \ln\left(\overline{Z}\right) dz \qquad (18)$$

where z is the position along the taper, L is the taper length, Z is the taper variation, Z_0 represents the reference impedance at the input end of the taper.

There are numerous solutions for (18) available for several characteristic impedance profiles (not strip width profiles) including exponential, linear, triangular [27], Klopfenstein [31], and Hecken [32] in order to increase the bandwidth. For example, for the exponential taper the input reflection coefficient can be obtained [27]:

$$\Gamma_{IN} = \frac{1}{2} Ln \frac{Z_L}{Z_0} e^{-j\beta L} \frac{\sin \beta L}{\beta L} \qquad (19)$$

This simplified solution (19) assumes TEM propagation mode for TL and both its characteristic impedance and propagation coefficient are distance-independent. Practically these parameters are changes along a line and propagation wave is not quite TEM. The actual two-section combined TL length then is shorter than λ/2 wavelength. For a maximum allowed reflection coefficient in the pass band the taper profile introduced by Klopfenstein has the shortest total length.

The reflection coefficient along a non-uniform TL can be described by a non-linear Riccati-type differential equation [33], which does not have a general analytical solution. The analysis can be based on numerical methods [34] or performed using electromagnetic analysis software, such as HFSS from Ansoft Corporation [35].

[This final part of this article series will appear in the nextissue of High Frequency Electronics. All references will be listed at the end of Part 3.]

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