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UHF RFID Antennas for Printer-Encoders— Part 1: System Requirements

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This three-part series presents a detailed overview of RFID encoder systems and the antenna solutions required for reliable printing (writing) to individual tags

This series of articles reviews UHF transmission line antennas developed for RFID Printer-Encoders. It explains the basic operating principles of antennas, their effect on the printer's encoding function as well as how the antennas influence the design of labels with embedded transponders (Smart Labels). The survey of antennas is preceded by the evaluation of antenna-transponder mutual coupling in reactive near-field and by the analysis of the Printer-Encoder environment, which yields four comparison criteria of the antennas' performance.

After discussing system requirements, the article covers two novel ultra-compact UHF antennas based on the tapered stripline transmission line, developed for the mobile RFID Printer-Encoders. These antennas enable the printers to encode short Smart Labels on a short pitch. The paper presents the development of the antennas, HFSS modeling, and an empirical study of their geometries, characteristic impedance and bandwidth. This type of UHF antennas used for stationary and portable RFID Printer-Encoders may be utilized by numerous item-level close proximity RFID applications.

1. Introduction

The Radio Frequency Identification (RFID) technology and its three major components (Readers, transponders and antennas) have experienced huge progress in the past ten years. Initially developed for aircraft identification in the 1940s, this technology has proliferated in almost all sectors of modern society. Manufacturing, pharmaceutical [1], healthcare [2], air luggage and supply-chain management, item-level identification for a variety of industries is a small number of the application fields.

With the exception of a completely automated system, HF or UHF passive transponders are rarely used by themselves. They are usually laminated with paper or plastic layers forming Smart Labels or Tags, which are able to communicate with RFID Readers. The name of the transponders, *passive* or *batteryless,* comes from the fact that the transponder is powered by energy transmitted by the Reader antenna. This power supports the Reader-transponder communication—the interrogation process—which includes writing data to the transponder's memory and retrieving previously stored information and/or the unique transponder identification data.

Most modern RFID applications require that the Smart Labels be readable by an optical scanner and a human being, in addition to the Reader. Consequently the Smart Labels containing the transponders often have printed bar codes and human readable text. The most convenient instrument to simultaneously print text, bar codes and encode Smart Labels is an RFID Printer-Encoder, which performs all three functions at the same time. Besides the labels, Smart plastic cards with embedded transponders have also become popular. High interest from credit card organizations in the Smart card technology [3] has driven the development of plastic card Printer-Encoders. Mandate-driven American and European markets and Asian manufacturing distribution centers require increasing quantities of HF and UHF RFID Printer-Encoders, Print Engine-Encoders for applicators, and mobile Printer-Encoders working with fork-lifts in the warehouses. In addition to the printing and the initial encoding purposes, this equipment is also widely used in the automated validation procedures for Smart Labels and cards, preventing their re-encoding and data corruption, continuously securing a smooth transition of many RFID pilot programs and extending the successes of existing applications.

Accelerated in the recent years, the evolution of the RFID technology and the hungry market for Printer-Encoders has fueled the development of specialized UHF antennas. Their ability to work with transponders in very close proximity and communicate selectively with only one targeted transponder, tightly spaced with others, essentially distinguishes the specialized UHF antennas from the conventional ones. In contrast to the antennas designed for long range RFID applications, these specialized antennas are very similar to RF bi-directional couplers based on electromagnetically coupled transmission lines [4] that are common in the RF and microwave realm. The difference from RF couplers is the variable distance between the coupled devices, the variability of transponder shapes, and a single RF port of the antenna-transponder structure.

Conventional antenna characterization parameters such as gain, radiation pattern, radiation power efficiency, directivity and beamwidth, which are normally used in antenna design for long range RFID applications, assume new meanings and definitions. For example, *beamwidth* becomes *transponder encoding range*, and *antenna directivity* becomes *spatial selectivity*. The antenna-transponder interaction occurs in a complex printer environment, which can disturb the nearby electromagnetic field, the antenna characterization parameters turn out to be dependent on the surrounding objects, transponder electrical parameters, and dimensions. Furthermore, the composite architecture of the Printer-Encoders creates an RF unfriendly environment, affects the transponders' interrogation process, and imposes limitations on the antenna dimensions and location. Most importantly, the Printer-Encoder and antenna designs also dictate the minimum acceptable size of the Smart Labels and their transponder placement. Because of these mechanical constraints the transponders cannot be placed arbitrarily in a Smart Label—their placement must be separately specified for every printer brand and model.

The Smart Labels specification, which dictates a particular transponder placement, indirectly expresses the RFID printer's encoding capability. A list of parameters describing transponders placement includes the *transponder placement range,* the *placement starting distance,* and the separation distance between the adjacent labels on a liner, known as the *pitch* (Fig. 1(a) and (b)).

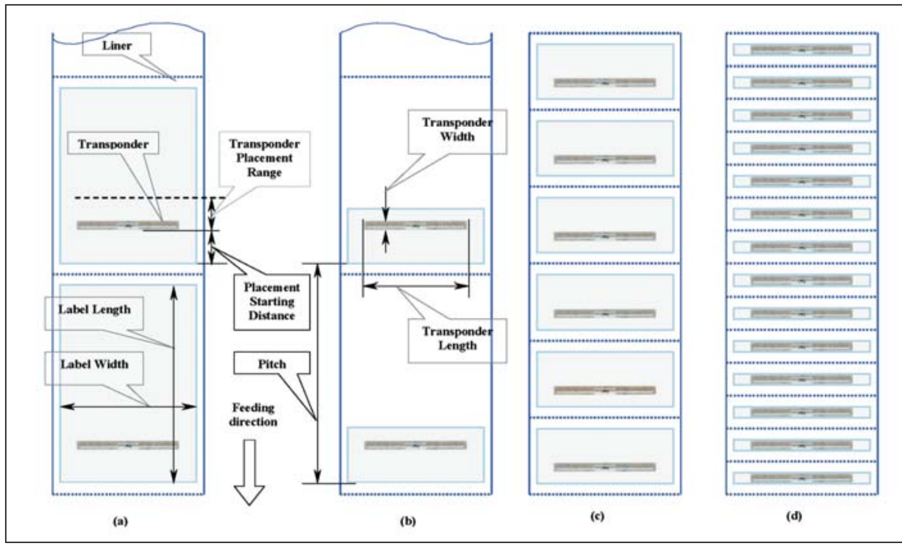

Figure 1 · Smart Label structure and transponder placement. (a) Smart Label design; (b) short labels with long pitch; (c) short Smart Labels; (d) small labels with short pitch.

When the dimensions of labels required for printing and encoding are 4" × 6" or 4" × 4" and their length significantly exceeds the transponder's width, or the labels are relatively short but far apart from each other (Fig. 1 (b)), the antenna can easily communicate with the targeted transponder without collision with the adjacent transponders. The complication and the challenge occur when the Printer-Encoder must encode short Smart Labels densely spaced on the liner (Fig. 1 (c) and (d)). In this case encoding a small component label requires an antenna with high *spatial resolution.* This attribute is the so-called spatial selectivity that is the antenna's capability to reliably interrogate the selected transponder without activating surrounding ones.

The ability of a printer to encode the transponders placed near the leading edge of the label defines the transponder *placement starting distance* and directly correlates with the antenna dimensions and its position inside the printer. The most challenging design goal is to make a printer-encoder capable of working with short Smart Labels, where the length of the Smart Label is nearly equal to the width of the embedded transponder (Fig. 1 (d)).

This review examines the capabilities and limitations of the different planar transmission line (TL) UHF antennas, which are used for RFID Printer-Encoders requiring the interrogation of a single transponder tightly spaced with other transponders and in very close proximity to the antenna. The review focuses on the low profile spatially selective mismatched stripline and double-conductor stripline TL antennas designed for printers capable of interrogating densely spaced short Smart Labels. The mismatched resonant TL antennas typically have a narrow bandwidth. To overcome this limitation a bandwidth improving technique originally developed for impedance matching TL transformers is applied to microstrip and stripline TL antennas. This article also presents an empirical verification of the antenna geometries and electrical parameters that were initially derived by using Ansoft High Frequency Structure Simulator (HFSS).

The ultra-compact stripline UHF antennas enable:

- Individual encoding of short Smart Labels with small pitch;
- Acceptance of transponders with broad deviations of resonance frequency and activation power thresholds;
- Positioning of the transponder placement area near the leading edge of the label;
- Printer batch mode encoding without involvement of the anti-collision management;
- Space saving design of the mobile RFID printers;
- Effortless installation and straightforward RFID conversion of the existing bar code printers.

The next section, *2. Antenna-Transponder Coupling in Close Proximity* examines magnetic and electric field distribution along the antenna-transponder structure, energy transfer and coupling mechanism between them. This section also identifies two criteria for comparison of field intensity and impedance bandwidth of the antennas.

Section *3. Printer-Encoder Environment* classifies four critical printer zones, relates their lengths to the constraints imposed by the antenna dimensions on the Smart Label design and transponder placement parameters, and establishes two geometrical criteria for antenna comparison.

Section *4. UHF Antennas for Stationary Printer-Encoders* presents a comprehensive review of several TL antennas developed for stationary UHF Printer-Encoders and qualitative analysis of their impact on the printer's encoding performance.

Section *5. UHF Antennas for Mobile Printer-Encoders* introduces the ultra-compact novel UHF stripline TL antennas, their strengths for mobile RFID Printer-Encoders, and optimization of the antenna geometries and electrical parameters using HFSS.

[Sections 3, 4 and 5 will be published in the October and November issues of High Frequency Electronics.]

2. Antenna-Transponder Coupling in Close Proximity

Although the UHF passive transponders produced by the leading vendors could have their antennas shaped similar to a meander-line [5], bow-tie [6], or cross dipole [7], the majority of them are half-wavelength dipole or folded-dipole antennas [5], [8], [9]. The dipole antenna is most popular in various RFID applications because of the near-omnidirectional radiation pattern in the far-field [10] and a straightforward chip impedance matching procedure [11]. The half-wavelength ($\lambda/2$), in free space, of an operational frequency 915 MHz (ISM US RFID band) is 164 mm. The physical length of the transponders may range from 120 to 20-25 mm depending on the permittivity of their substrate materials and the antenna profiles.

There are three spherical spaces surrounding the Reader and transponder antennas in the transmitting mode: reactive near-field, radiating near-field, and far-field [12, 13, 14, 15]. The radius of each sphere depends on the operational frequency (or wavelength) and the largest linear dimension (D) of the antennas. The interaction mechanism and the energy transfer between two antennas are determined by whether they are located within each other's near-field, radiating near-field, or far field. For the RFID 915 MHz frequency band the dimension D of antennas is usually chosen as one-half wavelength.

The far-field, having a propagating wave, starts outside the sphere with radius R_1, which can only be approximated [12] because of the violated condition $D > \lambda$.

$$R_1 > 2\frac{D^2}{\lambda}$$

Therefore, for an antenna with the largest linear dimension D = 164 mm, the radius of the sphere for far-field is R_1 > 164 mm and is smaller for shorter antennas.

When a transponder is located at distance R_1 or farther from the Reader's antenna, the electromagnetic components of the propagating wave and its impedance are independent of Reader antenna's geometry, and the field

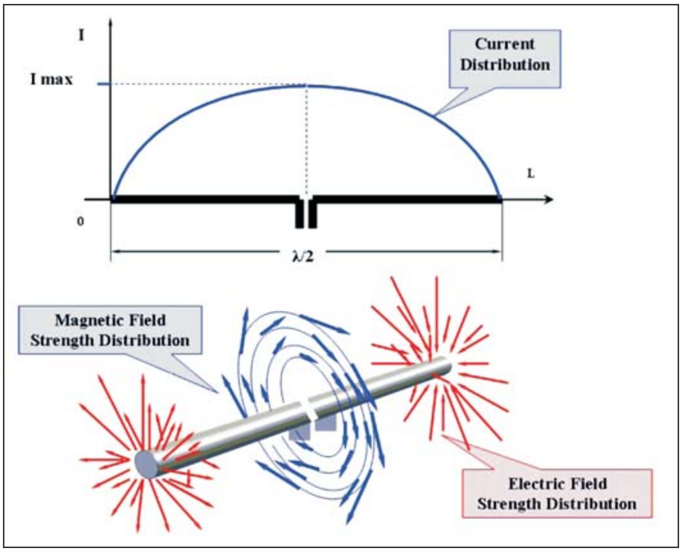

Figure 2 · Dipole current distribution and fields.

surrounding the transponder is uniform. In long range UHF RFID applications, where the transponders are several meters away from the Reader's antenna, they are in each other's uniform far-field. During data transmission the transponder varies the impedance of its antenna and changes its field, but these field disturbances do not affect the current distribution of the antenna in the transmitting mode or its electrical parameters. The antenna-transponder bi-directional communication is provided by the propagating wave, there is no coupling between them, and therefore no mutual influence.

Inside the sphere with the radius R_1 is the radiating near-field. The inner boundary of this region is approximated by the radius R_2

$$R_2 > 0.62\sqrt{\frac{D^3}{\lambda}}$$

For the frequency of 915 MHz and the half-wavelength antenna dimension D = 164 mm, the radius R_2 = 72 mm. This field is partly a product of the continuous electric and magnetic field energy exchange with the antenna, but predominantly is a radiation wave. The antenna is loosely coupled with the transponder and they have a weak mutual influence.

The region of the pure reactive near-field is within the estimated radius R_2. This field is the result of the continuous electric and magnetic field energy exchange with antenna electrical energy. The field strength is proportional to the antenna's Q-factor and the current flowing through it. For Printer-Encoders and other very close proximity applications the antenna-transponder separation distance is 5-10 mm and is much shorter than the linear dimensions of the Reader's or transponder's antennas.

The electro-magnetic components of an antenna's reactive near-field and its wave impedance vary significantly across the antenna's physical structure. The antenna and the transponder inside a Printer-Encoder operate in each other's non-uniform reactive near-fields.

The electric and magnetic field strength distributions for the half-wavelength transponder dipole antenna in the transmitting mode are depicted in Figure 2. In close proximity, the magnetic field is typically concentrated at the center of the dipole, where the current attains its maximum value, while the maximum electric field strength is at the edges of the dipole arms [17]. Applying the reciprocity theorem [12], which states that an antenna's transmitting performance is equal to its receiving performance, one can conclude that a Reader's antenna should have a similar to dipole electro-magnetic field distribution for the best coupling with a transponder.

The source of antenna's field is electric charges flowing through the antenna. Charges slowly moving in space create the reactive near-field and fast moving charges create the far-field [18]. At the UHF band the charges also vary in time with the period of 0.5 or 1 nanosecond. The temporal variation also contributes to the antenna's far-field radiation. The antennas radiated near-field and far-field strengths significantly increase if charges are spatially accelerated. Whenever a charge abruptly changes direction or vanishes, for example, because of the antenna's structure, the electrical energy applied to an antenna is efficiently converted into radiation [19]. The antenna's radiation efficiency increases when its length approaches the half-wavelength of its operational frequency. This explains why the radiation of the half-wavelength dipole antenna having zero current value at the ends of its arms is very efficient. High intensity radiation in the far-field is desirable for the long range RFID systems, which are based on propagating waves. But to be appropriate for very close proximity applications, an antenna should have a strong reactive near-field and a weak far-field to comply with the EMI/RFI regulations.

In very close proximity, the transponder activation energy is mostly delivered through the quasi-static electromagnetic coupling with the antenna. The coupling grade of two closely spaced devices depends significantly on their separation distance, geometrical profiles, and mutual alignment. Magnetic coupling is provided by mutual inductance [16] and electric coupling through static capacitances [4]. Mutual inductance is an attribute of closely spaced wires carrying current. The current through each antenna creates the corresponding magnetic flux that induces voltage and current in the other antenna. Static capacitance is an attribute of closely spaced conductive plates or areas having opposite charges. The antenna or transponder dipole's arms are these plates. The arms charges cause electric field strength variation and develop voltage across a nearby antenna and transponder constructing elements, which are in that field.

Transponders use a backscatter data transfer mechanism, re-radiating received signals back to the interrogator by their own antennas. For data transfer the transponder modulates the impedance of its own antenna and changes the surrounding antenna field distribution. This modulation influences the field of the Reader's antenna and in turn changes its current distribution, antenna impedance, and frequency tuning. An increase in separation distance reduces the grade of antenna-transponder electro-magnetic coupling.

The energy delivered to a transponder is used by the transponder's IC to support its interrogation. The RF power (P_T) delivered to a transponder is a product of its coupling grade with an antenna and the strength of the reactive near-field of the antenna powered by a Reader. Regardless of the antenna type the power P_T can be expressed by the equation:

$$P_T = K * P_A \qquad (1)$$

where K is a power transfer coefficient and P_A is Reader power applied to an antenna.

In the RFID systems with spatially independent and high value coefficient K, the power delivered to a transponder can considerably exceed its activation power threshold. The activation power threshold is the Reader's RF power level at which the transponder becomes energized and starts responding to the Reader's commands. This power threshold level is a complex function that depends on the antenna parameters, transponder IC impedance matching and its activation voltage threshold. Most importantly, the activation power threshold may depend on the transponder's location inside a printer. The excessive activation power causes a relatively extensive communication interval and substantially increases the transponder placement range (Fig. 1 (a)).

At disproportionate energy levels the reactive field will cover not only the targeted interrogation area but also the surrounding areas, which is not a problem when dealing with a single transponder, or when the transponders are spaced far apart. Although this spatial separation localizes the encoding interval, it also limits the minimum achievable label length. With closely spaced transponders, the interrogation range must be controlled so as to prevent accidental communications with the neighboring transponders. One way to prevent this collision is to reduce the Reader's power and consequently the length of the *transponder placement range.* In this case the delivered power is higher than the transponder's activation power threshold only for the encoding range and is lower than the activation power threshold outside of this range.

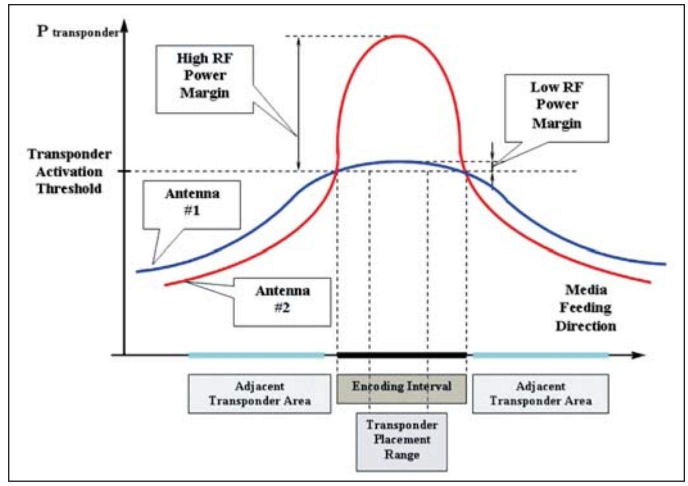

Figure 3 · Power delivered to a transponder and RF power margin.

Equation (1) demonstrates that the coefficient K, power P_A or both can be decreased for power reduction. For some types of antennas the coefficient K is independent of the antenna-transponder alignment and can be decreased to low power P_T. The drawback of lowering the coefficient K or power P_A is the loss of the RF power margin over the transponder activation power threshold for its placement range, as shown for Antenna #1 in Figure 3. The RF power margin is defined as the maximum suppression (in dB) of the Reader's operational RF power achieved in the middle of the *transponder placement range,* when the power falls to the transponder activation threshold level and the transponder stops communicating. With a low power margin the interrogation process becomes unreliable because of the system's susceptibility to the deviations of the transponder's and the antenna's electrical parameters and their precise tuning. Although some transponders with less than ideal parameters may have acceptable performance for long range applications, the power delivered in the near-field may become insufficient and the transponder will be missed. To stabilize the encoding process and make it robust, the RFID system should have the highest possible RF power margin.

In the RFID systems with spatially dependent coefficient K, its value changes depending on the antenna-transponder coupling grade, which correlates to the orientation and proximity to each other. For such a system, the coefficient K and the activation power achieve their maximum values only for the transponder which is closest to the antenna; they are noticeably lower for the adjacent transponders.

A tightly spaced antenna and transponder behave as an air-dielectric variable capacitor, which plates are formed by the transponder and the antenna. Its capacitance is proportional to the area of the overlapping surfaces of the antenna and the transponder. When the transponder moves closer to the antenna their mutual surface grows and the static capacitance increases. This increase in static capacitance improves the antenna-transponder coupling and raises the power delivered to the transponder as well. Similarly the magnetic coupling increases when the two current carrying "wires" move closer to each other. The power transfer coefficient varies along the communication range and the power delivered to the transponder throughout the *encoding interval* significantly exceeds the transponder's activation power threshold. In this case the RFID system has a high RF power margin, which is illustrated by the power curve for Antenna #2 in Figure 3.

For a selected antenna-transponder separation distance, an RFID system achieves the maximum RF power margin when their mutual overlapping area is comparable with the transponders' width. The limiting factor for the maximum grade of coupling is the impedance induced by the transponder in the antenna circuit. In very close proximity this induced complex impedance could cause a severe impedance mismatch between the Reader's and the antenna's ports leading to a drastic reduction of the transponder's activation power. To characterize the RF system power margin and the antenna-transponder coupling grade the *encoding field intensity* is introduced.

The coefficient *K,* in addition to being dependent on the antenna-transponder geometries and their alignment in the general case, is also a function of the antenna tuning frequency and the antenna impedance bandwidth (*BW*). To justify the antenna bandwidth, at least two aspects of the RFID system should be taken into account. The first one is the spectrum of modulated signals that are used by the Readers for transponders interrogation.

For 915 MHz U.S. RFID band, the allocated spectrum is 26 MHz ranging from 902 to 928 MHz. RFID uses frequency hopping modulation around the central frequency of 915 MHz. Although the Readers from different vendors operate at the same frequency band, they differ in their ability to handle hopping frequency phase shifts associated with phase difference of signals reflected from the antenna port for different channels. The Readers, which are based on I-Q synchronous detection of the transponder's re-radiated signals, typically require at their RF port a Standing Wave Ratio (SWR) of 1.4 or less in the operational band in order to perform reliable interrogation. The *BW* definition for conventional antennas is a frequency band over which an antenna has a SWR = 2 or has its reflection loss or S_{11} parameter that is less than –9.5 dB. The tuning frequency is the center of the antenna's bandwidth. To obtain a standard *BW* value of an antenna, the *BW* at SWR = 2 is calculated from the antenna *BW* at SWR = 1.4. For example, for a microstrip antenna, the following equation from [20] can be used:

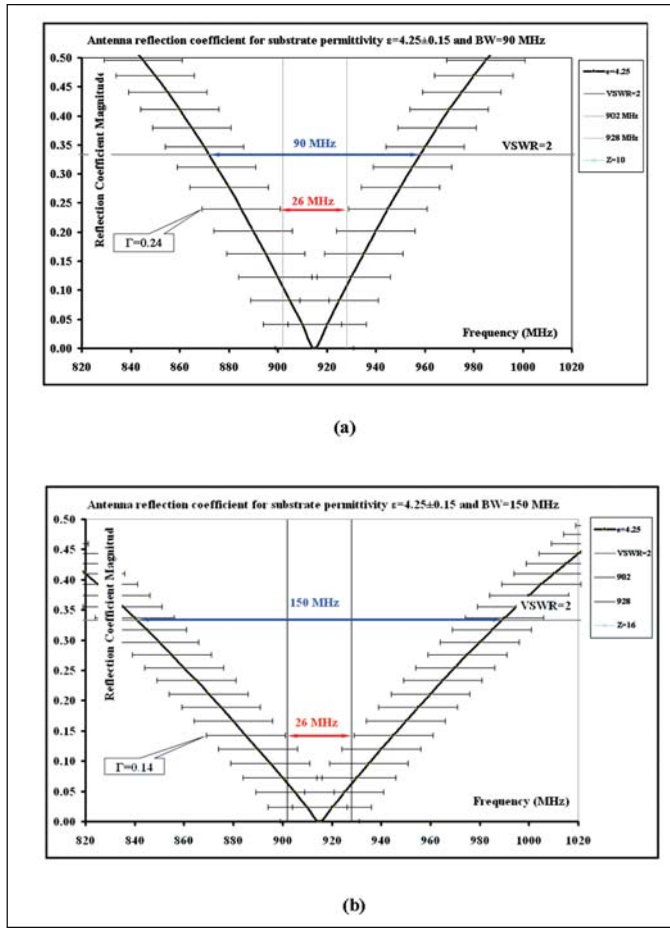

Figure 4 · Antenna reflection coefficient and impedance bandwidth (*BW*). (a) *BW* = 90 MHz; (b) *BW* = 150 MHz.

$$\frac{BW_1}{BW_2} = \frac{(SWR_1 - 1)}{\sqrt{SWR_1}} \times \frac{\sqrt{SWR_2}}{(SWR_2 - 1)} \qquad (2)$$

Substituting BW_2 = 26 MHz at SWR_2 = 1.4 and SWR_1 = 2 in Equation (2), we can find BW_1 = 54.4 MHz. This BW is derived for a precisely tuned 915 MHz antenna.

The second aspect of the RFID antenna's BW selection is associated with the deviations of antenna's electrical and mechanical parameters. The antenna fabrication process typically utilizes non-ideal materials and non-ideal operational procedures, which impact the antenna center frequency, port impedance, and consequently the input reflection coefficient (*Γ*). The reflection coefficient is related to *SWR* by the well-known formula:

$$\Gamma = \frac{SWR - 1}{SWR + 1} \qquad (3)$$

Using Equation (3) and SWR = 1.4, we obtain coefficient $\Gamma = 0.166$. This value can be used as the maximum acceptable level of reflection for the bandwidth. If the resonant frequency of a narrowband antenna changes noticeably, the antenna input reflection loss at the operational frequency increases, and the power transfer coefficient K drops. For example, a microstrip antenna based on the substrate material IS410 (ISOLA) with the dielectric constant $\varepsilon = 4.25 \pm 0.15$ and $BW = 90$ MHz can have a resonant frequency from 900 to 930 MHz (Fig. 4 (a)) and maintain an unacceptably high reflection coefficient $|\Gamma|$ below 0.24 ($SWR = 1.63$) for the 902-928 MHz frequency span instead of the $\Gamma = 0.166$ required for SWR = 1.4. If an antenna based on the same dielectric material has $BW = 150$ MHz, its reflection coefficient magnitude is $|\Gamma| < 0.14$ for the 902-928 MHz band (Fig. 4 (b)) and it complies with the Reader SWR requirements.

Deviations of other antenna parameters including the thickness of the substrate and the copper cladding have less influence on the antenna resonant frequency than the dielectric constant and the BW of 150 MHz can be considered as a conservative estimate for the desirable antenna bandwidth in order to tolerate technological deviations of the antenna's electrical and mechanical parameters. On the other hand, an excessive antenna bandwidth is not advantageous. Antennas with substantially wider than necessary bandwidth could potentially be susceptible to the electro-magnetic interferences caused by the printer's nearby electrical and electronic devices. The chosen *impedance bandwidth* criterion thus represents a characteristic of the antenna in terms of the technological stability and the EMI/RFI immunity.

[This article will continue in the next two issues of High Frequency Electronics, beginning with with section 3. Printer-Encoder Environment. All references will be listed at the end of the final installment.]

Author Information

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