

# RC-Loaded Bow-Tie Antenna for Improved Pulse Radiation

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**Abstract**—In this paper, a loading technique for improving pulse radiation from bow-tie antennas is introduced. This technique allows transmission of short transient pulses with very small late-time ringing and relatively high radiation efficiency. It makes use of a combination of a constant resistive loading along the antenna and a capacitive loading with linearly increasing reactance toward the antenna ends. The constant resistive loading is applied using volumetric microwave absorbers to cover one side of the antenna and the linear capacitive loading is realized by constructing narrow slots on the antenna surface. Relatively high radiation efficiency is achieved by choosing the location of the slot nearest to the feed point in such a way that radiation from it combines constructively with radiation from the feed point. Using a 0.8-ns monocycle for excitation, the technique results in a level of late-time ringing of lower than  $-40$  dB and at the same time the peak value of the transmitted pulse is 54% higher than that of the same antenna without loading.

**Index Terms**—Bow-tie antennas, capacitive loading, resistive loading, ultrawide-band antennas.

## I. INTRODUCTION

IN THE PAST FEW decades impulse ground penetrating radar (GPR) has received increasing attention in a wide range of subsurface probing applications, in which short transient pulses are used as the probing signals. It is commonly understood that in GPR applications for detection of shallowly buried objects, it is essential that the probing pulses contain very small late-time ringing in order to prevent masking of targets.

Late-time ringing is caused mainly by multiple reflections between the antenna open ends and feed point, which indicate the narrowband nature of the antenna. The most-widely used technique for enlarging antenna bandwidth (thus reducing late-time ringing) is the application of resistive loading, in which the well-known Wu–King profile [1] can be used to determine the loading distribution along the antenna. The main disadvantage of resistive loading is that it considerably reduces radiation efficiency. In the case of the Wu–King profile it has been shown that radiation efficiency decreases to as low as 23% [2]. To avoid this drawback the use of nondissipative reactive loading has been proposed. Nyquist and Chen suggested inserting a pair of lumped reactive elements to enlarge antenna bandwidth about a

certain frequency by placing the elements at an optimal distance from the antenna ends [3]. Several investigators have proposed improved methods using distributed capacitive loading with different loading profiles, which includes constant [4], linear [5], and exponential [6] profiles. In addition, a combination of resistive and capacitive loading with Wu–King [7] and empirically determined [8] profiles have also been introduced. It has been verified that capacitive loading keeps radiation efficiency 100%, a combination of resistive and capacitive loading gives radiation efficiency between 40% and 60% (depending on the profile), and resistive loading can in some cases drop the radiation efficiency down to 30% [9]. However, it has been shown that resistive loading is the most effective one for suppressing late-time ringing, while capacitive loading (alone or in combination with resistive loading) still exhibits a relatively high level of ringing [9]. Furthermore, difficulties in the practical realization of nonlinear loading profiles (e.g., Wu–King) on a planar structure such as a bow-tie antenna have been indicated [10].

In this paper we propose a loading technique for transmitting short transient pulses with very small late-time ringing and relatively high radiation efficiency, which is intended mainly for an implementation on a bow-tie antenna [11]. The technique employs a combination of resistive and capacitive (RC) loading with constant and linear profiles, respectively, and is mainly aimed at impulse GPR applications, in which the antenna is situated close to or in contact with the ground. The novelty of this technique lies in three aspects:

- 1) Realization of a constant resistive and linear capacitive loading by a combination of volumetric microwave absorbers and narrow slots on the antenna surface.
- 2) Introduction of a one-side loading scheme, in which only one side of the antenna is resistively loaded.
- 3) Utilization of the slot nearest to the feed point for improving radiation efficiency.

Aspect no. 1 results in a very low level of late-time ringing, aspect no. 2 minimizes the negative influence of resistive loading on radiation, and aspect no. 3 significantly increases the peak value of the transmitted pulses.

## II. DESIGN OBJECTIVES

In this paper, the targeted applications are impulse GPR for detection of small objects near the interface (e.g., road inspection and landmine detection). In such applications, it is of utmost importance that the probing pulses are transmitted with minimal late-time ringing, as radar returns mostly fall within the time window of the ringing. Moreover, because of the lossy nature of soil, it is essential to transmit the pulses with high efficiency.

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In view of the above, we state the main objectives of this work as follows:

- 1) We wish to transmit pico- or nano-second pulses with minimal late-time ringing using a bow-tie antenna for GPR applications. The level of the ringing should be lower than  $-40$  dB (1%) with respect to the maximum amplitude (peak value) of the transmitted pulse.
- 2) We wish to transmit the pulses with high efficiency. It means that the peak value of the transmit waveform should be as high as possible.

The above statements stipulate that resistive loading alone should not be used as it degrades radiation efficiency. Therefore, we need to develop an alternative loading technique that will satisfy the mentioned objectives. As capacitive loading alone cannot suppress late-time ringing [9], we will resort to a combination of resistive and capacitive loading. In addition, we mention that for the targeted applications in general it is not a necessity to transmit the replica of the exciting pulse. The transmit waveform may instead resemble the first derivative of the exciting pulse.

### III. A METHOD FOR APPLYING $RC$ LOADING TO BOW-TIE ANTENNAS

To satisfy the design objectives stated above, in this paper we investigate an alternative  $RC$  loading with constant and linearly increasing profile for respectively the resistive and the capacitive loading. An analytical expression for the current distribution on a dipole due to the  $RC$  loading has been derived and it has been shown in the frequency domain that the  $RC$  loading effectively suppresses currents near the ends of the dipole [12], [13]. Moreover, a transient analysis of the dipole has demonstrated the effectiveness of the  $RC$  loading for late-time ringing suppression [13].

In this paper, we propose a method for implementing the  $RC$  loading on a circular-end bow-tie antenna. The proposed method can be described by the following recipes:

- 1) The circular-end bow-tie antenna should be constructed as a printed antenna on a substrate (e.g., epoxy). The capacitive loading with linear profile can then be realized by photo-etching concentric slots on the antenna surface. It has been shown that in this case the capacitances across the slots decrease almost linearly with the slot widths [14]. Thus, to approximate linearly increasing reactance toward the ends, the slot widths should also increase linearly toward the ends. Note that as the performance of a capacitive loading depends on the frequency range of interest, the optimal slot widths are dependent on the exciting pulse.
- 2) The resistive loading can be realized by covering the conducting (printed) side of the antenna with volumetric microwave absorbers. Hence, the equivalent surface resistance on the antenna is determined by the strips between two adjacent slots. More specifically, the equivalent surface resistance per square meter is inversely proportional to the area of the strips. Thus, to realize resistive loading with constant profile, the area of the strips should be made equal along the antenna. It has been shown that despite the fact that the volumetric absorbers cover only one side of the antenna, the results have been found to be satisfactory in

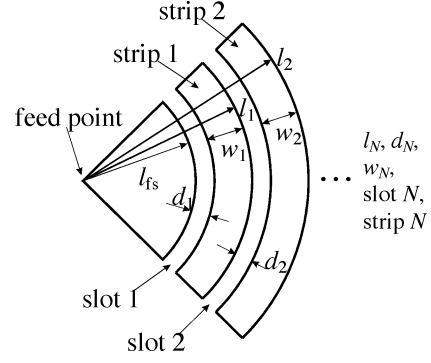


Fig. 1. Geometry of the circular-end bow-tie antenna with concentric slots for realizing a capacitive loading. Only one arm of the antenna is shown. The flare angle is  $90^\circ$ .

TABLE I  
SLOT AND STRIP WIDTHS OF THE EXPERIMENTAL BOW TIE

$n$	$l_n$ (mm)	Slot width $d_n$ (mm)	Strip width $w_n$ (mm)	$n$	$l_n$ (mm)	Slot width $d_n$ (mm)	Strip width $w_n$ (mm)
0	10	-	-	24	130	2.5	2.5
1	15	0.2	4.8	25	135	2.6	2.4
2	20	0.3	4.7	26	140	2.7	2.3
3	25	0.4	4.6	27	145	2.8	2.2
4	30	0.5	4.5	28	150	2.9	2.1
5	35	0.6	4.4	29	155	3.0	2.0
6	40	0.7	4.3	30	160	3.1	1.9
7	45	0.8	4.2	31	165	3.2	1.8
8	50	0.9	4.1	32	170	3.3	1.7
9	55	1.0	4.0	33	175	3.4	1.6
10	60	1.1	3.9	34	180	3.5	1.5
11	65	1.2	3.8	35	185	3.6	1.4
12	70	1.3	3.7	36	190	3.7	1.3
13	75	1.4	3.6	37	195	3.8	1.2
14	80	1.5	3.5	38	200	3.9	1.1
15	85	1.6	3.4	39	205	4.0	1.0
16	90	1.7	3.3	40	210	4.1	0.9
17	95	1.8	3.2	41	215	4.2	0.8
18	100	1.9	3.1	42	220	4.3	0.7
19	105	2.0	3.0	43	225	4.4	0.6
20	110	2.1	2.9	44	230	4.5	0.5
21	115	2.2	2.8	45	235	4.6	0.4
22	120	2.3	2.7	46	240	4.7	0.3
23	125	2.4	2.6	47	245	4.8	0.2

Note:  $l_0 = l_{fs}$

terms of late-time ringing suppression [13]. In this way, we introduce a one-side loading scheme, which finds its importance especially for transient applications. Its main advantage lies in the fact that the absorbers degrade radiation from the covered (printed) side only, while radiation from the uncovered (substrate) side is only slightly affected (this will be shown later). For GPR applications, the uncovered side is thus chosen to be the side facing the ground.

3) The slot nearest to the feed point introduces a discontinuity on the antenna surface and because of this it becomes a secondary source of radiation. Objective no. 2 in the previous section can be achieved by determining the location of the slot nearest to the feed point in such a way that the radiation from it combines constructively with the radiation from the feed point in the broadside direction of the antenna. In this way,

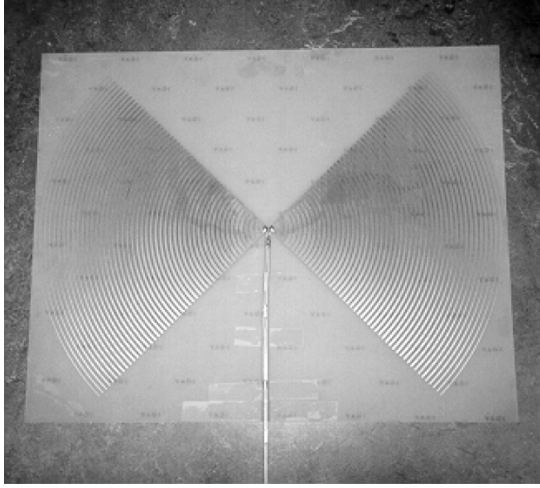


Fig. 2. Experimental circular-end bow-tie antenna with linear capacitive loading constructed on an epoxy substrate with slot and strip widths given in Table I. Length  $\approx 50$  cm, flare angle =  $90^\circ$ .

improvement of the peak of the resulting transmit waveform can be obtained in the broadside direction of the antenna.

#### IV. DETERMINATION OF LOADING PARAMETERS

Before implementing the proposed loading scheme on a practical bow-tie antenna it is imperative first to discuss how the loading parameters are determined. In particular, we need to determine the widths of the slots and the strips to realize the resistive and capacitive loading along the antenna. Furthermore, it is also important to investigate the optimal distance between the feed point and the first slot for increasing the peak value of the transmitted waveforms. The geometry of the considered bow tie is depicted in Fig. 1.

##### A. Determination of Slot and Strip Widths

In this paper, the proposed loading technique is implemented on a circular-end bow-tie antenna with a length of about 50 cm. The flare angle is chosen to be  $90^\circ$ .

According to recipe no. 1 in the previous section, the slot width  $d$  should be determined to be linearly increasing toward the ends to obtain the required capacitive loading with linearly increasing profile. On the other hand, to create the constant resistive loading suggested by recipe no. 2, it is shown that the strip width  $w$  should be chosen to be linearly decreasing toward the ends. As mentioned above, by reducing  $w$  toward the ends the surface area in strip  $n$ , with  $n = 1, 2, \dots, N$ , can be kept equal for all  $N$  strips to obtain constant values of equivalent resistance/ $\text{m}^2$  along the antenna after placing an absorber on the antenna surface.

As there is no easy way to precisely determine the values of the capacitance across the slots and the resistance on the strips,  $d$  and  $w$  are instead determined intuitively. The first slot width,  $d_1$ , is determined to be 0.2 mm, which is the smallest value of  $d$  that can be realized using conventional photo-etching technology. In [12] and [13] based on the theoretical analysis of the RC loading we have suggested that the value of impedance at the antenna ends is  $25 \text{ j k}\Omega/\text{m}$ . Here, we select antenna half-length  $\lambda$  to equal 25 cm and the feed point-first slot distance  $l_{fs}$ , to equal

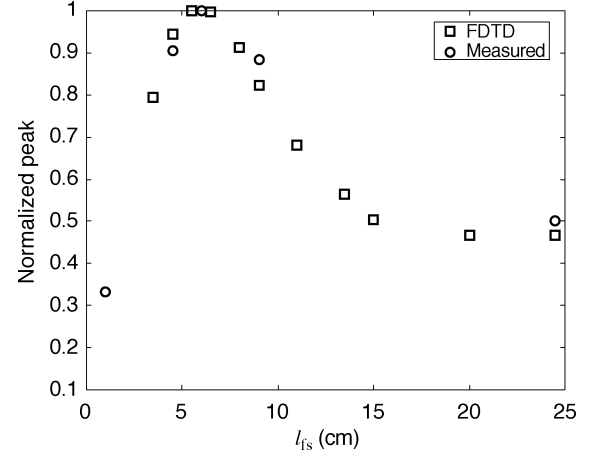


Fig. 3. Normalized peak value of the pulse transmitted in the broadside direction by the slotted bow-tie antenna in Fig. 2 as a function of the feed point-first slot distance  $l_{fs}$ . The exciting pulse is a monocycle with 0.8-ns duration.

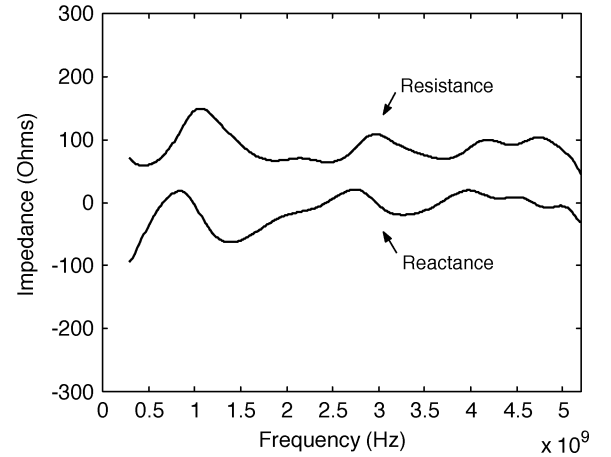


Fig. 4. Input impedance of the RC loaded bow-tie antenna in free space. The feed point-first slot distance  $l_{fs} = 6$  cm.

1 cm. Hence, at a distance of 1 cm from the feed point the value of the impedance should be  $1 \text{ j k}\Omega/\text{m}$  and this value should increase  $1 \text{ j k}\Omega/\text{m}$  per cm along the antenna. Thus, assuming  $d_1 = 0.2 \text{ mm}$  corresponds to an impedance of  $1 \text{ j k}\Omega/\text{m}$ , we set  $d_N = 25 \times d_1 = 5 \text{ mm}$ , which should correspond to a value of impedance of  $25 \text{ j k}\Omega/\text{m}$  at the end of the antenna. Furthermore, to create a relatively smooth variation in the reactance, the increase in slot width,  $d_{n+1} - d_n$ , is chosen to be 0.1 mm.

The strip width  $w$  is determined to vary in a similar fashion, but in the opposite direction. The last strip width  $w_N$  is also determined to be 0.2 mm as this is the smallest value of  $w$  that can still be realized by photo etching in a conventional manner. The decrease in strip width,  $w_n - w_{n+1}$ , is also chosen to be 0.1 mm. Hence, with  $d_1 = w_N = 0.2 \text{ mm}$ ,  $d_{n+1} - d_n = w_n - w_{n+1} = 0.1 \text{ mm}$ ,  $l_{fs} = 1 \text{ cm}$  and  $\lambda = 25 \text{ cm}$ , we arrive at the number of slots/strips ( $N$ ) = 47. In Table I the 47 values of  $d$  and  $w$  are listed. By inspection it is found that the ratio of the surface area in strip 47 to that in strip 1 is about 1.23, indicating that the surface area in the strips is relatively constant along the antenna. The experimental antenna has been constructed on a thin epoxy substrate and is shown in Fig. 2.

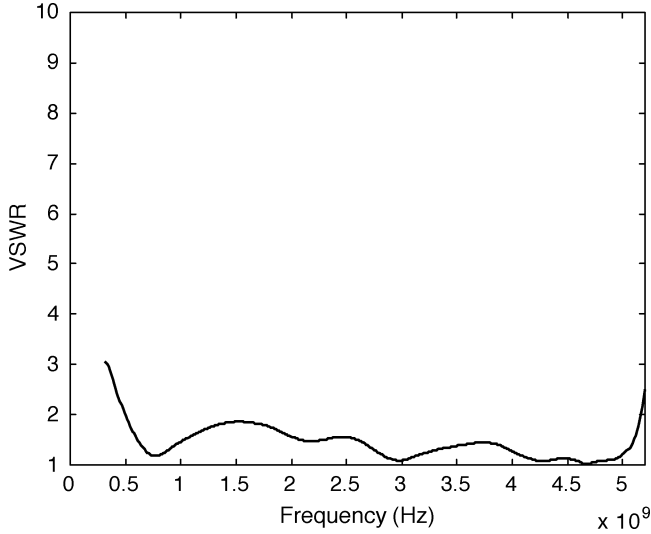


Fig. 5. VSWR of the RC loaded bow-tie antenna in free space fed by a 100-Ohm feed line. The feed point-first slot distance  $l_{fs} = 6$  cm.

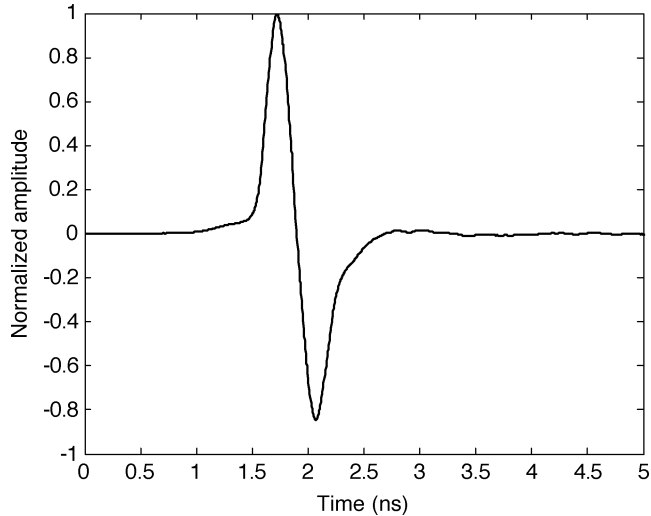


Fig. 6. Exciting pulse: a monocycle with 0.8-ns duration.

### B. Determination of the Feed Point-First Slot Distance

According to recipe no. 3 in the previous section, to enhance radiation efficiency, feed point-first slot distance  $l_{fs}$  should be selected for which in the broadside direction the pulse radiated from the feed point combines constructively with the pulse radiated from slot 1. The value of  $l_{fs}$  for which the resulting waveform would have the highest peak value in the broadside direction can be inferred from common understanding of general antenna properties, to immediately arrive at

$$2l_{\max} = \frac{c_{\text{subst}}}{2f_c} \quad (1)$$

where  $l_{\max}$  is the value of  $l_{fs}$  that corresponds to the highest peak value of the transmitted pulse,  $c_{\text{subst}}$  is wave velocity in the substrate and  $f_c$  is the central frequency of the exciting pulse that corresponds to the maximum in the spectrum of the pulse. As the precise value of  $f_c$  for the 0.8-ns monocycle used for excitation is 830 MHz and the relative permittivity of epoxy is around 3, by means of (1) we find the value of  $l_{\max}$  to be

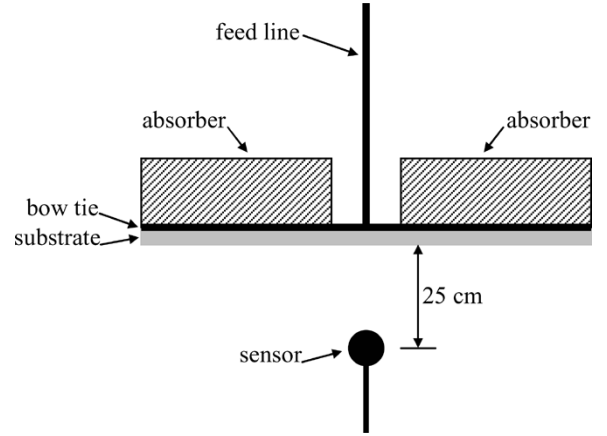


Fig. 7. Setup for waveform measurements in free space (side view).

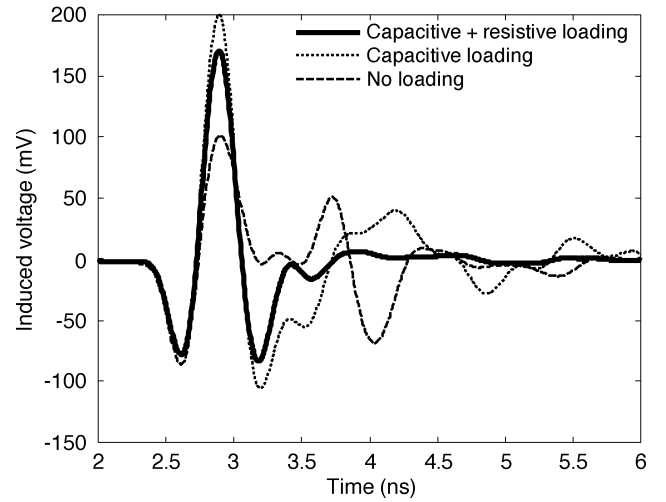


Fig. 8. Free-space transmit waveforms due to different loading schemes for  $l_{fs} = 6$  cm. The observation point is 25 cm from the antenna (in the broadside direction).

about 5.5 cm. To verify this result, several circular-end bow ties with  $90^\circ$  flare angle and different lengths are modeled using the finite-difference time-domain (FDTD) method and the pulses transmitted in the broadside direction are computed. In addition, an experimental verification is carried out by short-circuiting the slots of the antenna in Fig. 2 to obtain different values of  $l_{fs}$ . The computed and measured results for the 0.8-ns monocycle are presented in Fig. 3 where both of the simulation and the measurement confirm that the value of  $l_{\max}$  is indeed in the neighborhood of 5.5 cm. Additionally, we notice that as  $l_{fs} = 25$  cm corresponds to the case when the antenna is not loaded, Fig. 3 indicates that  $l_{fs} = l_{\max}$  leads to doubling of the peak value of the transmit waveform.

## V. EXPERIMENT

In the measurements use of a balun is avoided by using a feed line constructed from a pair of identical 50-Ohm semi-rigid coaxial cables, which are soldered together over their length. The bow-tie antenna in Fig. 2 is fed by connecting the inner conductors at one of the line's ends to different apexes of the bow tie. The semi-rigid cables at the other end of the line are connected to different channels of the measuring equipment

TABLE II  
PEAK OF TRANSMIT WAVEFORM FOR  $l_{fs} = 6$  cm

Loading	Peak (mV)	Peak (%)	Peak (dB)
Capacitive	200.1	100	0
Capacitive + resistive	170.6	85.3	-1.4
No loading	101.0	50.5	-5.9

(a network analyzer for frequency-domain measurements or a sampling scope for time-domain measurements). Hence, this feeding method is equivalent to feeding the antenna using a 100-Ohm balanced line.

#### A. Input Impedance

Foam-based volumetric microwave absorbers have been utilized to create the resistive loading by placing them on the conducting (printed) surface of the bow-tie antenna in Fig. 2. The measured input impedance of the resulting RC loaded bow-tie antenna in free space is presented in Fig. 4 for  $l_{fs} = 6$  cm ( $n = 10$ ), which according to Fig. 3 would give the highest peak value of the transmitted waveform. This value of  $l_{fs}$  has been obtained by closing the slots for  $n \leq 10$  using a piece of copper foil. In Table I we can see that in this case the first slot width = 1.2 mm and the first strip width = 3.8 mm. The voltage standing wave ratio (VSWR) due to the 100-Ohm feed line is shown in Fig. 5. It is shown that the VSWR of the antenna is smaller than 2:1 (corresponding to a reflection coefficient of 0.333 or -9.54 dB) in the frequency range of 0.495–5.155 GHz, indicating a bandwidth of more than 4.6 GHz for this level of VSWR.

#### B. Transmit Waveform

For measuring the waveforms transmitted by the RC loaded bow-tie antenna in free space we made use of an ultrawide-band sensor [15] located 25 cm from the antenna (in the broadside direction). The antenna is excited by a monocycle with duration of 0.8 ns shown in Fig. 6. The adopted measurement setup is illustrated in Fig. 7 where it can be seen that the conducting layer, on which the slotted bow tie is printed, is embedded in between the absorbers and the substrate.

The waveform measurements have been performed for three loading schemes: 1) the antenna is only capacitively loaded (no absorbers); 2) the antenna is capacitively and resistively loaded (with absorbers); and 3) the antenna is not loaded. For the last one we used a bow-tie antenna of the same dimension without slots and absorbers.

The induced voltage measured at the sensor's terminal for  $l_{fs} = 6$  cm is presented in Fig. 8. It is obvious that when the antenna is only capacitively loaded, the peak of the waveform is maximal. However, the level of late-time ringing is in this case unacceptably high. By introducing the resistive loading in the antenna it is shown that the ringing is considerably reduced. When the antenna is not loaded, a strong reflection at the ends is clearly visible in the figure. We also observe that in this case the peak value of the waveform is about one half of the highest peak value, as suggested by Fig. 3. The absolute and relative values of the waveform peaks due to the above three loading schemes

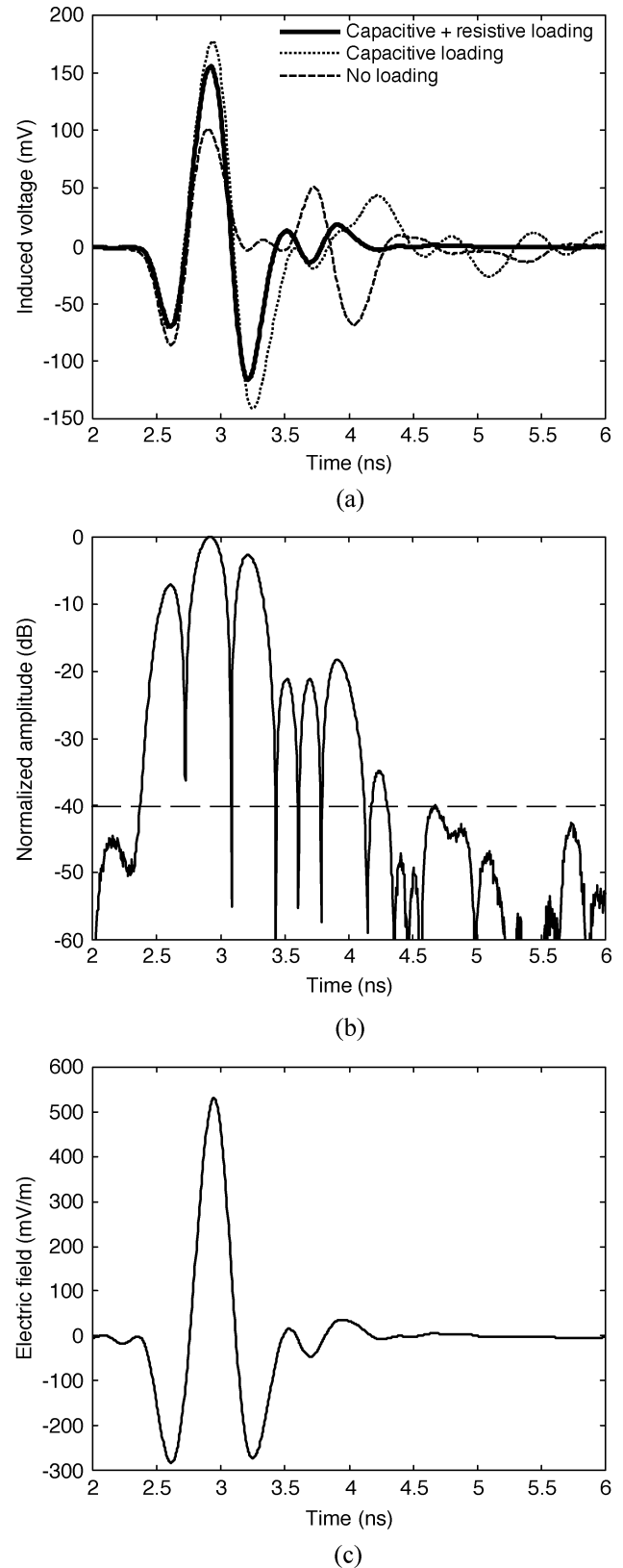


Fig. 9. (a) Free-space transmit waveforms due to different loading schemes for  $l_{fs} = 9$  cm. The observation point is 25 cm from the antenna (in the broadside direction). (b) The result with solid line in (a), given in decibels. (c) The result with solid line in (a) after removing the sensor's influence.

for  $l_{fs} = 6$  cm are given in Table II. It can be seen that the introduction of the resistive loading reduces the peak only by

TABLE III  
PEAK OF TRANSMIT WAVEFORM FOR  $l_{fs} = 9$  cm

Loading	Peak (mV)	Peak (%)	Peak (dB)
Capacitive	176.9	100	0
Capacitive + resistive	155.4	87.9	-1.1
No loading	101.0	57.1	-4.9

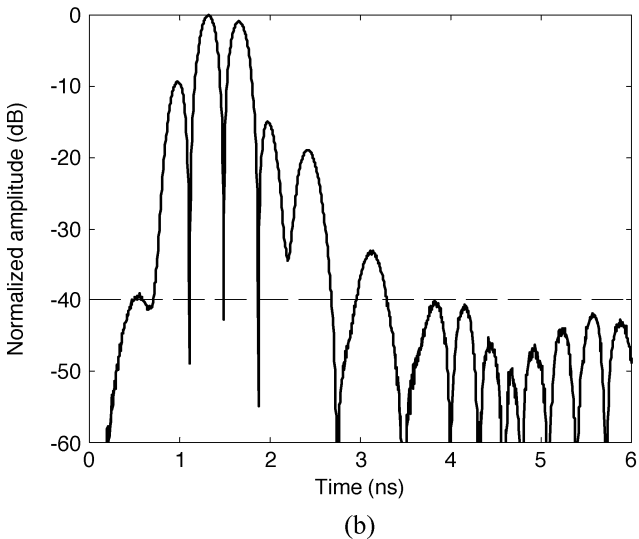
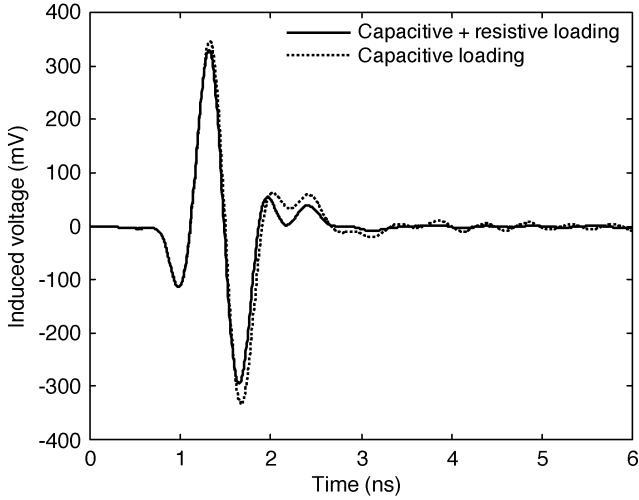


Fig. 10. (a) Subsurface transmit waveforms due to different loading schemes for  $l_{fs} = 6$  cm. The observation point is at a 16-cm depth in the broadside direction of the antenna. (b) The result with solid line in (a), given in decibels.

14.7%. The waveform peak due to the  $RC$  loading is still 69% higher than that in the case without loading.

Although the late-time ringing in Fig. 8 is already substantially reduced by the  $RC$  loading, objective no. 1 in Part A of Section II is not yet satisfied as the level of the ringing is still higher than  $-40$  dB. To further reduce the level of the ringing, we carried out an optimization process by varying feed point-first slot distance  $l_{fs}$ . As mentioned above, this has been performed by short-circuiting the slots near the feed point. Due to such an engineering approach, it has been found that the level

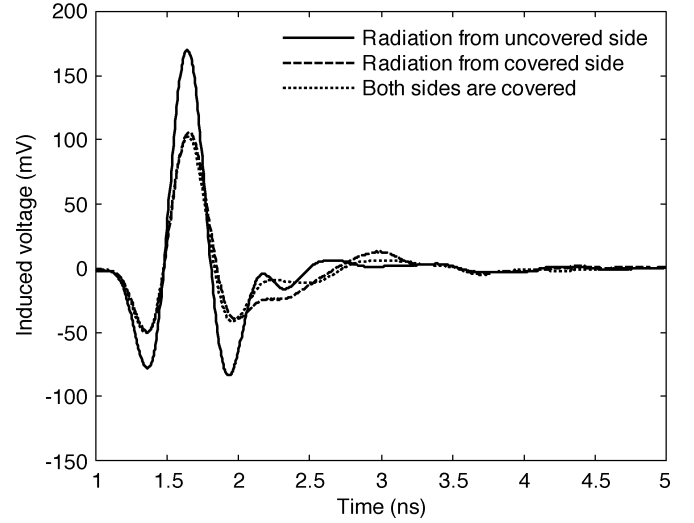


Fig. 11. Waveforms radiated from different sides of the  $RC$  loaded bow-tie antenna. The antenna is covered with foam-based absorbers on the conducting (printed) side. The solid curve is the same as that in Fig. 8. The dashed curve is the waveform radiated toward the opposite direction (from the side with absorbers) at the same distance (25 cm) from the antenna. The dotted curve is obtained when both sides are covered with the absorbers.

of ringing lower than  $-40$  dB could be achieved by setting  $l_{fs} = 9$  cm ( $n = 16$ ) when the  $RC$  loading was employed. The transmit waveforms due to this value of  $l_{fs}$  for the three loading schemes are presented in Fig. 9(a). As indicated by Fig. 3, in this case the peak of the transmit waveforms becomes slightly lower than the highest peak due to  $l_{fs} = 6$  cm shown in Fig. 8. The reduction of the peak is a trade off for a lower level of late-time ringing demonstrated in Fig. 9(a) by the solid line. To observe this more clearly, in Fig. 9(b) the result is plotted in decibels, where it is obvious that the oscillation in the tail of the waveform starting from 4.3 ns (or less than 2 ns from the beginning of the pulse) is already contained below the  $-40$  dB level. The absolute and relative values of the waveform peaks due to the three loading schemes for  $l_{fs} = 9$  cm are given in Table III. It is shown that introduction of the resistive loading reduces the peak only by 12.1%. The peak due to the  $RC$  loading is found to be still 54% higher than that in the case without loading. With this result the two objectives set in Section II are satisfied. In addition, to check how far the waveforms are affected by the sensor characteristics, the sensor's influence on the waveform due to the  $RC$  loading in Fig. 9(a) is removed using a deconvolution procedure developed in [15]. The resulting waveform, given in Fig. 9(c), is the radiated electric field at the sensor's location. It can be seen that the shapes of the waveform before deconvolution [the sensor's output, in volts, in Fig. 9(a)] and after deconvolution [the radiated electric field, in volt/meter, in Fig. 9(c)] are essentially the same, indicating the replicating property of the sensor.

Furthermore, we carried out measurements of subsurface transmit waveforms, for which the antenna was situated horizontally above dry sand having relative permittivity  $\epsilon_r \approx 2.5$  and very small conductivity. The measurement setup similar to the one given in Fig. 7 was adopted, with the only differences being the substrate side of the antenna touching the ground and the sensor buried 16 cm below the interface.

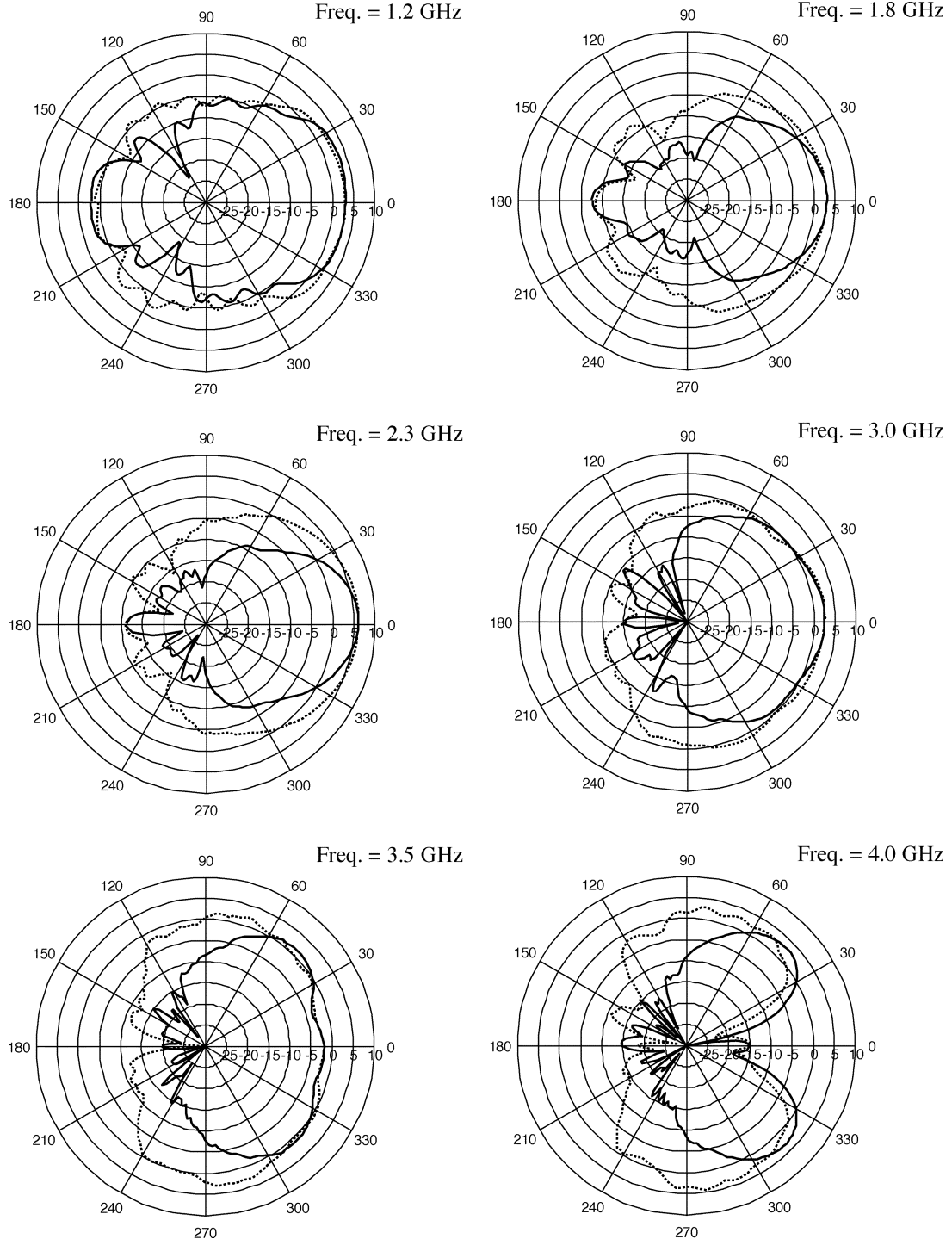


Fig. 12. Radiation patterns of the RC loaded bow-tie antenna ( $l_{fs} = 6$  cm) for different frequencies, measured in dBi. The solid and dotted curves correspond to the patterns in the E-plane and H-plane, respectively.

In this measurement, we were mainly interested in the antenna configuration that provides minimal late-time ringing ( $l_{fs} = 9$  cm). However, to account for the presence of the ground,  $l_{fs}$  should be reduced by a factor of  $\sqrt{\epsilon_r}$ . Here, we reduced  $l_{fs}$  to 6 cm. The results due this value of  $l_{fs}$  are presented in Fig. 10(a) for two different loading schemes. The results show that the ground plays an important role in improving the performance of the capacitive loading. It can be seen in the figure that in this case capacitive loading alone already gives

much reduced ringing in comparison with the free-space results in Figs. 8 and 9. This is caused by the fact that the ground acts as a natural resistive loading due to its finite conductivity. Using the volumetric absorbers to increase the resistive loading, an improved result is obtained as shown in Fig. 10(a). In Fig. 10(b) it is demonstrated that the achieved level of late-time ringing starting from about 3.2 ns is also lower than  $-40$  dB.

Recipe no. 2 in Section II claims that by using absorbers only on one side of the antenna, the absorbers degrade radiation from

the covered (printed) side, while radiation from the uncovered (substrate) side is only slightly affected. The basis of this claim can be seen in Fig. 11, as an example, where the transmit waveform due to the  $RC$  loading for  $l_{fs} = 6$  cm in Fig. 8 (solid curve) is copied. The waveform radiated toward the opposite direction of the antenna (thus radiated from the side covered with absorbers) at the same distance (25 cm) from the antenna is plotted in Fig. 11 as a dashed curve. It is evident that in this case the peak value of the waveform degrades considerably. In the figure the peak is shown to be about 30% lower than that of the solid curve. When compared with the waveform radiated by the bow tie without absorbers (the dotted curve in Fig. 8) the peak is nearly 50% lower. Additionally, it is shown by the dotted curve in Fig. 11 that placing the absorbers on both sides of the antenna neither degrades the peak value further nor minimizes the late-time ringing.

### C. Radiation Pattern

The free-space radiation patterns of the  $RC$  loaded bow-tie antenna have been measured in an anechoic chamber that operates properly at frequencies of 1.2 GHz and higher. It should be noted that to minimize the effort spent in the construction work for mounting the antenna with absorbers in the chamber, in these measurements we have been forced to employ relatively thin foam-based absorbers, which might not function effectively to provide adequate amount of resistive loading.

The measured radiation patterns of the  $RC$  loaded bow-tie antenna ( $l_{fs} = 6$  cm) at 6 different frequencies from 1.2 to 4 GHz are presented in Fig. 12. The results clearly demonstrate the directive property of the antenna in the E-plane due to the presence of the absorbers at the backside of the antenna. Moreover, the figure shows that the main beam of the antenna is relatively stable for frequencies up to 3 GHz and that the gain in the broadside direction is relatively stable for frequencies up to 3.5 GHz. It is shown that the main beam breaks up at 4 GHz as at this and higher frequencies one may expect the radiation mechanism of the antenna to behave unfavorably since the slot and strip widths are not designed to operate at such high frequencies.

## VI. CONCLUSION

A loading scheme for improving pulse radiation by bow-tie antennas is proposed. The loading scheme allows transmission of short transient pulses with very small late-time ringing and relatively high radiation efficiency. The loading consists of a capacitive loading with linearly increasing reactance toward the antenna ends and a constant resistive loading along the antenna. The technique has been successfully implemented on a bow-tie antenna in free space as well as above a lossy ground. A level of late-time ringing of lower than  $-40$  dB is achieved and at the same time the peak of the transmitted pulse is 54% higher than that of the same antenna without loading. It is shown that a VSWR smaller than 2:1 is obtained in the frequency range of 0.5–5.1 GHz. However, for frequencies above 4 GHz the antenna will not radiate in a favorable manner.

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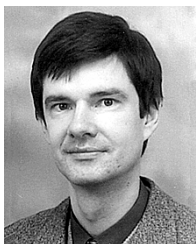
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