Prediction formulas for a notched frequency response of a printed ultra-wideband antenna loaded with notching resonators

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Abstract: This Letter presents closed-form formulas for fast approximate determination of frequency band notches of ultra-wideband (UWB) antennas loaded with nearly quarter-/half- or even full-wavelength notches resonators. The formulas are derived using the curve-fitting technique. They describe the influences of the physical length of these notches resonators on the corresponding frequency notches in the UWB of 3.1–10.6 GHz. The calculated results obtained using these new formulas show good correlation with the reported electromagnetic simulation results elsewhere.

1 Introduction

Since the Federal Communication Commission of the US assigned 3.1–10.6 GHz frequency band of ultra-wideband (UWB) systems in February 2002 [1], UWB technology has been attracting considerable interests in both the academic and commercial domains. These interests of using UWB systems are increased nowadays because of the potentially high-data rate (more than 110 Mbits/s) for short range, low-power consumptions and easy to different devices such as wireless universal serial bus, personal computers, high-definition TVs etc. Consequently, UWB antennas have received more and more attention, as the only non-digital part of UWB system.

The use of the UWB antennas have more challenges to meet, namely, stable radiation pattern, gain and group delay, all over the operated band. Covering this ultra-wide bandwidth arouses a co-existence interference problem with narrowband technologies sharing with UWB some of the frequency bands such as worldwide interoperability for microwave access operating in the band 3.3–3.7 GHz and wireless local area network operating in the band 5–6 GHz, and more existing standard UWB systems. To overcome this problem and avoiding interference, UWB antennas use filters to suppress these dispensable bands. An alternative approach to notch-out specific frequencies is to design UWB antenna with frequency band-notched characteristics.

With the development of UWB antenna having frequency band-notched features, literature is congested with different designs in various topologies. However, the most popular method to obtain the notched band is to insert resonators such as slots or parasitic strips. The length of any of these resonators may appear to be nearly a quarter-/half- or a full-wavelength of the corresponding resonance frequency [2].

The aim of this Letter is to present approximated closed-form expressions to help researchers and UWB antenna designers to fast determine the frequency band-notched responses of the nearly quarter-/half- or full-wavelength resonators introduced in the UWB antennas. The formulas are obtained by means of curve-fitting technique which gives the best fit equation with the available data [3]. The formulas describe a relationship between the total length of a resonator and the corresponding notched frequency. To verify the proposed approach, the results obtained from the presented approximated formulas are compared with the simulation results obtained previously for some band-notched UWB antennas in the literature [4]. The validity of the proposed technique is verified and high-accuracy results are obtained.

2 Theory and formulation

To find the best fit expression, various sets of simulated traces data are required. The presented band-notched UWB antennas in literature are utilised to extract the required band-notch response data. Various resonators lengths of nearly a quarter-/half- and a full-wavelength embedded in UWB antennas are used.

Based on various sets of simulation traces and estimating lower- and upper-frequency limits of each resonator response in the UWB frequency band, closed-form formulas for the total length of the resonator, L_t as a function of frequency can be developed through the use of the principle of the polynomial curve-fitting expressions.

As a first order of approximation, the dimensions of the resonator can be chosen according to the following formula

$$L_t = \frac{\lambda_g}{n} \tag{1}$$

where L_t is the effective length of the resonator, λ_g is the guided wavelength at the desired notch frequency and $n = 1$, 2 and 4 are corresponding to a nearly full-, half-, and quarter-wavelength, respectively.

The guided wavelength can be approximately calculated by the formulas as follows [5]

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \tag{3}$$

where λ_0 is the wavelength in the free space and ε_{eff} is the effective relative dielectric constant.

Therefore the notch frequency, f_{notch} is given by

$$f_{notch} \simeq \frac{c}{nL_t\sqrt{\varepsilon_{eff}}} \tag{4}$$

Using the curve-fitting technique, the relationship between the notched frequency, f_{notch} and the total length of the nearly quarter-/half-and full-wavelength resonators according to parametric studies can be approximated by second-order polynomial as follows

$$L_{t(\lambda/4)} \simeq 0.26(f_{\text{notch}})^2 - 4.9(f_{\text{notch}}) + 27 \quad 3 \le f_{\text{notch}} \le 11 \quad (5)$$

$$L_{t(\lambda/2)} \simeq 0.51(f_{\text{notch}})^2 - 9.7(f_{\text{notch}}) + 55 \quad 3 \le f_{\text{notch}} \le 11 \quad (6)$$

$$L_{t(\lambda)} \simeq (f_{\text{notch}})^2 - 19.4(f_{\text{notch}}) + 110 \quad 3 \le f_{\text{notch}} \le 11 \quad (7)$$

where L_t in mm and f_{notch} in GHz.

These various expressions all stem from the same underlying principle and it can be observed that the relation for one specific formula can be derived from that for the others.

The proposed closed-form formulas to calculate the notched frequency are validated by comparing the calculated results with the simulated results obtained from the electromagnetic (EM) simulator. Fig. 1 shows the comparisons between the calculated results obtained from the proposed formulas and the simulated results of the notched frequency response for the nearly quarter-/half- and full-wavelength notch resonators presented in [4]. The proposed formulas are valid in limited space according to the lower-and upper-frequency limits of the resonator response in the UWB frequency band, whereas the effect of the resonator disappears elsewhere.

From the illustrated results in Fig. 1, it can be observed that the deviation between the slopes of the curve-fitting formulas and the slopes of the simulated results is very small and acceptable. With smooth tunings, the exact length of the notched resonator can be found for sharp rejection skirt which depending on the specific antenna geometry and the EM numerical technique used to design and optimise the antenna's modelling.

Open-ring resonator (ORR) is one of the most common resonating elements (slot/parasitic strip) used to notch-out specific frequencies in the UWB frequency band, because of its advantages of compact size, easy fabrication, narrow pass bandwidth and low-radiation loss [6]. The effective physical length of the ORR, can be calculated as $l = 2\pi r_{\text{ext}} - g$ (r_{ext} is the external radius of the ORR and g is the gap width, which are used to optimise the band-notch performance). The resonance of the ORR is caused by its effective length which matches a multiple of a half-wavelength, with a small discrepancy because of the curvature of the particle [7].

Using second-order polynomial based curve-fitting technique and according to parametric studies, general expressions for the band-notch response of the total length of the nearly half-wavelength ORR in the UWB frequency band, in terms of its

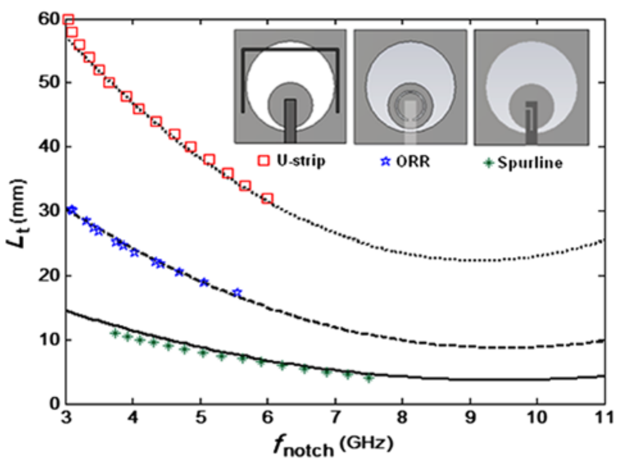

Fig. 1 *Comparison between the calculated and simulated values of the notched frequencies for various total lengths, L_t of notched resonators obtained from proposed formulas and those presented in [4]*
—— Nearly quarter-wavelength resonators, (5), ----- nearly half-wavelength resonators, (6) and …. nearly full-wavelength resonators, (7)

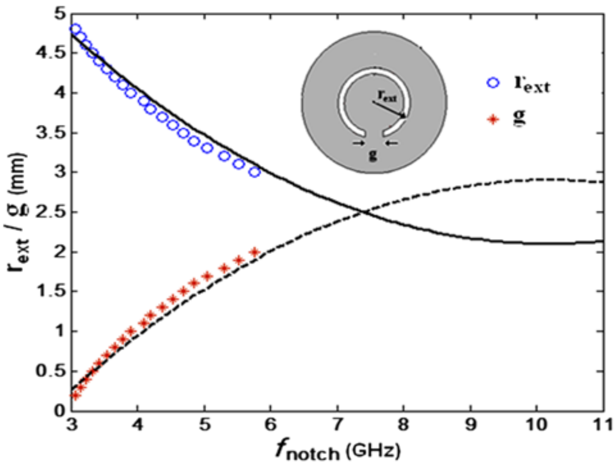

Fig. 2 *Comparison between the calculated and simulated values of the notched frequencies for various external radii, r_{ext} and gap widths, g of the notched ORR obtained from the proposed formulas and those presented in [4]*
—— External radius (r_{ext}), (8) and ----- gap width (g), (9)

external radius, r_{ext} and gap width, g can be approximated as

$$r_{\text{ext}} \simeq 0.051(f_{\text{notch}})^2 - 1.04(f_{\text{notch}}) + 7.4 \quad 3 \le f_{\text{notch}} \le 11 \quad (8)$$

$$g \simeq -0.051(f_{\text{notch}})^2 + 1.04(f_{\text{notch}}) - 2.4 \quad 3 \le f_{\text{notch}} \le 11 \quad (9)$$

To validate the proposed formulas, Fig. 2 shows the comparison between the calculated results obtained from the proposed formulas and the simulated results of the notched frequency response for the nearly half-wavelength ORR presented in [4]. It is depicted that the simulation results are in well correlation with the theoretical predictions based on these expressions. In practice, because of limited space in the miniaturisation of the ORR geometry, the lower limit of r_{ext} of the ORR may be limited to almost 2.5 mm where it equals to the value of g which corresponds to the notched frequency at, almost, 7.5 GHz.

3 Conclusion

In this Letter, new and simple approximated closed-form formulas for computing the frequency band-notched responses of UWB antennas loaded with nearly a quarter-/half- or a full-wavelength notch resonator are presented. The formulas are obtained by means of the curve-fitting technique. They are useful for fast describing the influences of the total length of the notched resonators on the corresponding notched frequencies in the UWB frequency range. The formulation is done through the use of a second-order polynomial. Using this process, a fast and precise determination of frequency band-notched response of an UWB antenna loaded with notch resonators can be achieved without the need to perform the time-consumed tuning parametric studies on these notched structures. Calculated results accomplished with discussion are presented. The theoretical results obtained by using these new formulas are with very good agreement with the simulated results reported in the literature.

4 References

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