Decoupling of Dipole Antennas by a Split Loop

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Abstract. The decoupling of two very closely located resonant dipoles by a similar dipole located in the middle between them has been recently demonstrated. An approximate analytical model of this decoupling was built, validated by exact numerical simulations and confirmed experimentally. In this work we show that the similar decoupling can be achieved using another scatterer, namely a split-loop resonator may nicely replace the dipole. This replacement allows us to broaden the operation band of the antenna system nearly twice.

1. Introduction

A complete passive decoupling of two resonant dipole antennas 1 and 2 separated by an arbitrary gap \( d \) (the minimal value of \( d \) is restricted only by the requirement \( d \gg r_0 \), where \( r_0 \) is the wire cross section radius) was suggested and studied theoretically and experimentally in \cite{1}. The decoupling is achieved by placing a similar resonant but passive dipole 3 (half-wave straight wire) in the middle of the gap. Then the electromotive force (EMF) induced by dipole 1 in dipole 2 is compensated by a part of the electromotive force induced in dipole 2 by scatterer 3. Similarly, scatterer 3 when excited by dipole 2 compensates the EMF induced by dipole 2 in dipole 1. This decoupling is complete, meaning that the power flux from dipole 1 to dipole 2 (and vice versa) is substituted by the flux from these dipoles to the scatterer for whatever relations between currents in dipoles 1 and 2. They both can be active, one of them can be active whereas the other can be loaded at the center by a lumped load or can be shortcut, they remain decoupled. However, this decoupling is approximate in the meaning that the power flux between dipoles 1 and 2 is suppressed not completely. For practical applications it is enough to reduce the mutual power transmittance by 10-12 dB. However, the bandwidth of antennas may suffer of the presence of scatterer 3. This is the case of \cite{1}, when the band of the resonant lossless matching (when the antenna circuits are tuned at the decoupling frequency) shrunk seven times due to passive dipole 3; and the bandwidth of the decoupling regime was as narrow as the resonance band. The purpose of the present study is to find a decoupling scatterer for two dipole antennas separated by a gap \( d < \lambda/30 \) as compact and efficient as the half-wave straight wire but more broadband. We will show that it can be achieved using an elongated split loop resonator at the same frequency as dipoles 1 and 2. We called this scatterer split-loop resonator (SLR).
2. Theoretical prerequisites

Now let us prove that decoupling of dipoles 1 and 2 located in free space is possible with an SLR symmetrically located between them. Since the loop contour \( C \) comprises the gap \( g \) we may consider the SLR as a wire scatterer. The method of induced EMFs is applicable to our SLR, as well as it was applicable to the dipole of our previous work [1]. Therefore, the condition of the complete decoupling expressed by formula (12) of work [1]

\[
Z_{13}^2 = Z Z_M \tag{1}
\]

remains valid for the structure whose side view is shown in Fig. 1. Here \( Z_M \) is mutual impedance between dipoles 1 and 2, \( Z \) is the self-impedance of our SLR, and \( Z_{13} = Z_{23} \) is its mutual impedance with antenna 1 or antenna 2.

Figure 1. The side view of the structure comprising two active dipoles 1 and 2 (not seen behind) driven by arbitrary external voltages \( V_1 \) and \( V_2 \) and the passive SLR 3 between them whose self-impedance \( Z_{33} \) and mutual impedance \( Z_{13} = Z_{23} \) with the dipoles 1 and 2 refers to the Reference section. Current \( I_3 \) induced in the SLR is the sum of the electric \( I_e = 0.5I_0f_e(z) \) and magnetic \( I_m = \pm 0.5I_0f_m(z) \) modes. At \( (y = +h/2, \; z = 0) \) \( I_m = I_e = I_0/2 \), at \( (y = -h/2, \; z = 0) \) \( I_m = -I_e = -I_0/2 \).

A primary source \( V_1 \) in the center of dipole 1 induces in our SLR 3 two current modes – an electric one \( I_e \) symmetric and an antisymmetric magnetic one \( I_m \) with respect to the plane \( y = 0 \). If the current in the reference section of the SLR i.e. at point \( (y = +h/2, \; z = 0) \) is denoted as \( I_0 \) both modes have the same amplitude \( I_0/2 \) at this point, whereas they mutually cancel each other at the gap that can be approximated by point \( (z = 0, \; y = -h/2) \). The distribution of the electric dipole mode along the SLR is similar to that in a straight wire. Contrary to the electric mode, the magnetic one is maximal at the vertical sides of the loop. This is so because these sides are shortcuts if our SLR is considered as a two-wire line. This model of the loop results in the following approximation:

\[
f_e(z) \equiv \frac{I_e(z)}{I_0/2} = \frac{\sin k \left( \frac{L}{4} - |z| \right)}{\sin \frac{kL}{4}}, \quad f_m(z) \equiv \frac{I_m(z)}{I_0/2} = \frac{\pm \cos k \left( \frac{L}{4} - |z| \right)}{\cos \frac{kL}{4}}. \tag{2}
\]

Sign plus corresponds to the top side of the loop \( (y = +h/2) \), sign minus – to the bottom side \( (y = -h/2) \). We analytically calculate the mutual impedance \( Z_{13} \) between dipole 1 and SLR 3 applying the general formula of the induced EMF method:

\[
Z_{13} = \frac{1}{I_1} \int_C E_{13}(l)f_3(l) \, dl, \tag{3}
\]
where $I_1$ is the current at the center of dipole 1, $E_{13}(l)$ is the tangential component of the electric field produced by this primary current at a point $l$ of the wire contour $C$ of scatterer 3, and $f_3(l) = f_e(l) + f_m(l)$ is the current distribution in scatterer 3. Decomposition of the current induced in 3 onto the electric and magnetic modes allows us to split the right-hand side of (3) into electric and magnetic mutual impedances formed by the coupling of the primary current $I_1$ with the electric and magnetic modes, respectively. The analytical calculation of the integrals was done using the saddle point method. In this integration we essentially use the assumption that the SLR and the dipoles are resonant (and their resonance bands overlap).

In the case $h \ll d$ Eq. (1) – decoupling condition – transforms into a simple relation from which we find the detuning $\gamma$

$$\beta \gamma = \left( \frac{\eta k L_1^2}{d R_0} \right) - 1$$

and check is this detuning really corresponds to the resonance band of both dipole 1 (or 2) and SLR 3. Choosing as an example $L_w = 500$ mm and $r_0 = 1$ mm (then the resonance band of dipoles 1 and 2 centered by the resonance frequency can be specified as 290-310 MHz) we fit the resonance band of the SLR to that of the dipoles when $h = 10$ mm and $L_l = 290$ mm. For $d = 3$ cm (in this case $h = d/3$) and $L_l = 29$ cm (4) yields $\gamma \approx 0.0423$ that implies the decoupling at the upper edge of the resonance band – at 312.8 MHz. Of course, the model is approximate and it is an approximate decoupling, however, in our terminology it is complete since should be observed for whatever relations of currents in the active dipoles.

3. Validation

Our experimental and numerical results are presented in Fig. 2. The complete decoupling implies that it is achieved for arbitrary relations between currents in the antennas. It is enough to inspect the decoupling for two different relations, corresponding to the mismatched and matched dipole antennas. In both mismatched and matched regimes (Figs. 2(a) and 2(b), respectively), minima of $S_{12}$ were simulated at 312.8 MHz that is the indication of the complete decoupling. Due to the difficulty of the tunable matching circuit, we measured the S-parameters only for the mismatched structure. Our measurements agree very well with simulations and can be considered as a confirmation of the theory.
Our simulations for the matched case show that the insertion of SLR 3 decreases $S_{12}$ at 312.8 MHz by 10 dB (from -4 dB corresponding to the reference structure [1] to -14 dB). This is probably sufficient for many applications. The operational band of the decoupled system can be defined as the minimal one of two bands – that of the matching (the band where $S_{11} \leq -15$ dB using a lossless matching circuit) and that of the decoupling (the band where $S_{12} \leq -10$ dB). In these definitions both bands of the matching and decoupling are equal to 1.3 MHz. This band is much wider than that offered by a decoupling dipole in [1] and this broadening is the main practical result. It follows from the fact that the extra mismatch due to the presence of the SLR at the distance $d/2$ from our antennas is not as high as the extra mismatch due to the presence of the dipole scatterer. We have not compared the simulation results of decoupling by passive SLR and dipole because the decoupling frequency is not the same for these cases; however, the enhancement of operating band is clear from comparison of $S_{11}$ in Fig. 2(a) with $S_{11}$ in Fig. 3 of paper [1].

4. Conclusions
We theoretically and experimentally showed the complete passive decoupling of two very closely located resonant dipoles achieved by adding a passive scatterer different from the similar dipole. Decoupling is granted by a long and narrow split loop, having the resonance in the same frequency band as the dipole antennas. The usefulness of this technical solution is the enlarged operation band of the antenna system.

References
[1] M. S. M. Mollaei, A. Hurshkainen, S. Glybovski, and C. Simovski, “Passive decoupling of two closely located dipole antennas,” submitted to IEEE Trans. Antennas Propag., available in arxiv: 1802.07500.

Acknowledgment
This work was supported by the Russian Science Foundation (Project No. 18-19-00482).