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Phase Conjugation of Double Periodic Arrays of Nonlinearly Loaded Straight Wires Based on Nonlinear Currents Approach

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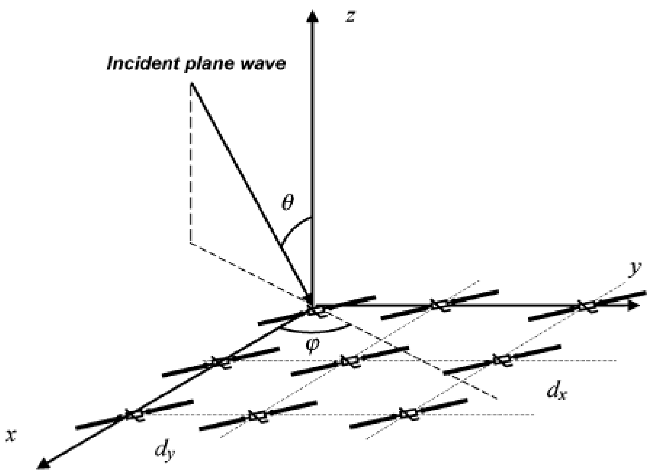
Abstract
In this paper, double periodic arrays of nonlinearly loaded wires are efficiently analyzed. The analysis is based on predicting formulae extracted from nonlinear currents approach. The proposed formulae are applied to infinite arrays of nonlinearly loaded wires under oblique incidence. The simulation results show that the induced voltage at mixing harmonic frequencies are in excellent agreement with harmonic balance technique. As an application, the phase conjugation via this modeling approach is investigated which is in agreement with the accurate approach.

Keywords: periodic array, nonlinearly loaded straight wire, nonlinear current approach

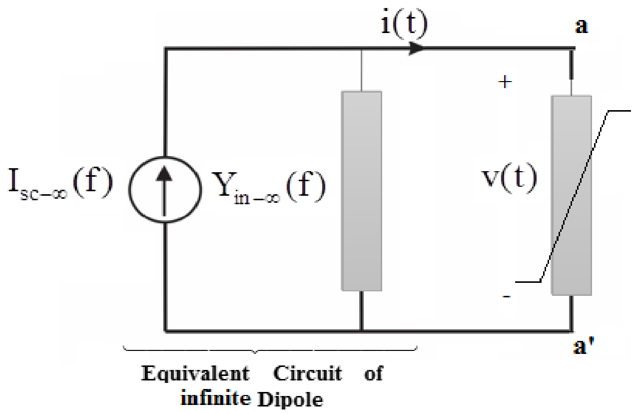
Introduction

As known, nonlinearly loaded antennas in single and array arrangements (called also nonlinear antennas) can be used to control scattering response (as frequency selective surface or FSS) or to protect receivers against high-valued signals such as lightning strokes. There are several attempts either in frequency domain [1-10] or in time domain [11-13]. On one hand, time domain methods are more accurate than the frequency domain ones, they, however, cannot be used in the presence of lossy ground easily. Frequency domain methods, on the other hand, are efficient, but they are suffering from truncation error especially when the spectral content of incident wave includes too many frequency components such as lightning electromagnetic pulses (LEMP).

Figure 1(a) shows a typical infinite array of nonlinearly loaded wires as well as frequency-domain equivalent circuit in figure 1(b). In this figure, $Y_{in-\infty}$ and $I_{sc-\infty}$ denote respectively input admittance and short circuit current of Norton's equivalent circuit viewed across each dipole terminal. These two quantities are computed via applying numerical methods such as method of moments (MoM) [14] on Maxwell's equations. Frequency-domain approaches such as harmonic balance [1] are based on solving this equivalent circuit in somehow so that the induced voltage is computed at mixing harmonic frequencies. Such a structure as reported in [15] can be used as phase-conjugated FSS in communication networks.



(a)



(b)

Figure 1 (a): Infinite array of dipoles centrally loaded with nonlinear load. Adapted from [15], (b): frequency-domain equivalent circuit of infinite array of nonlinearly loaded antennas. Adapted from [5].

This property utilizes the nonlinear properties of the array through which the wavefront to be phase conjugated passes in order to produce a signal replica. This replica signal will propagate in the exact reverse propagation direction to that of the original signal since the overall phase of each partial plane wave in the wave packet has been reversed. Consequently the phase conjugated wavefront retraces then the original path of the incoming wave front but in the reverse direction.

With reference to [15], a comprehensive analysis using a complex hybrid method based on combining MoM and Volterra series was proposed, and the effects of incident angle and the spacing among antennas on the phase-conjugated property was investigated.

Among frequency-domain approaches proposed by Lee et al [1-10], an efficient approach based on nonlinear currents approach for computing induced voltage at mixing harmonic frequencies was introduced [5]. This approach in despite of Volterra series results in extracting the induced voltage at mixing harmonic frequencies separately and efficiently. This approach seems that it can be used in analysis of such structures efficiently. To show capability of this approach, the effects of incident wave angle and the spacing among antennas on the phase-conjugated property of nonlinearly loaded wires are investigated and then compared with the ones in [15].

This paper is organized as follows. In section II, the problem formulation based on nonlinear currents approach is briefly explained. Section III is focused on applying the proposed approach on the problem under consideration. Finally concluding remarks are given in section IV.

Modeling Principles

In this section, the approximate modeling approach is only applied on the single nonlinearly loaded wire. Analysis of infinite arrays of nonlinearly loaded wires can be similarly carried out using the infinite periodic structure green function [16]. In dealing with such structures based on nonlinear current approach, the nonlinear load is first represented as power series, i.e.

$$i = g_1 v + g_2 v^2 + g_3 v^3 + ... \quad (1)$$

The voltage in (1) can be expressed as

$$v(t) = v^1(t) + v^2(t) + v^3(t) + ... \quad (2)$$

Where $v^{(k)}(t)$ represents the sum of all mixing frequency components of k-th order. If the voltage across the nonlinear load is limited to third order, the current $i(t)$ in (1) can be divided into linear term $i_{linear}(t)$ and nonlinear term $i_{nonlinear}(t)$ as bellow

$$i_{linear}(t) = g_1 v(t) \quad (3)$$

$$i_{nonlinear}(t) = g_2 v^2(t) + g_3 v^3(t) \quad (4)$$

The linear part in (1) represents a linear resistor with resistance of $1/g_1$. If the nonlinearity of the load is limited to third-degree then the mixing frequency components of third order are as bellow

$$i_{nonlinear}(t) = \{g_1 v^{(1)}(t)^2\} + \\ + \{2g_2[v^{(1)}(t)][v^{(2)}(t)] + g_3[v^{(1)}(t)]^3\} \quad (5)$$

The above equation can be divided into the second-order mixing component $i^{(2)}(t)$, and third-order mixing component $i^{(3)}(t)$, i.e.

$$i_{nonlinear}(t) = i^{(2)}(t) + i^{(3)}(t) \quad (6)$$

Where

$$i^{(2)}(t) = g_2[v^{(1)}(t)]^2, \quad (7)$$

$$i^{(3)}(t) = 2g_2[v^{(1)}(t)][v^{(2)}(t)] + g_3[v^{(1)}(t)]^3 \quad (8)$$

According to (7) and (8), the nonlinear equivalent circuit in figure 1(c) can be redrawn as shown in figure 2.

The goal of the analysis is to obtain the terminal voltage of each dipole. Using the substitution theorem and setting all the current sources except $i_{sc}(t)$ to be zero initially, i.e., $i^{(2)}(t) = 0$ and $i^{(3)}(t) = 0$, one can obtain the voltage component from the contribution of $i_{sc}(t)$ only. This voltage component is regarded as $v^{(1)}(t)$ in (7) and (8). The total iteration sequence is given as

$$\begin{array}{l|l} v^{(1)} & \rightarrow i^{(2)}(t) \rightarrow v^{(2)}(t) \rightarrow i^{(3)}(t) \rightarrow v^{(3)}(t) \\ \text{linear} & \Leftarrow \text{nonlinear part (method of nonlinear currents)} \end{array} \quad (9)$$

For instance, assume that we have a multi-tone excitation

$$i_s(t) = \sum_{q=-Q}^{+Q} I_q^s e^{j\omega_q t} \quad (10)$$

By setting all the current sources except $i_{sc}(t)$ to be zero initially, one can obtain

$$v^{(1)}(t) = \sum_{q=-Q}^{+Q} V_q^{(1)} e^{j\omega_q t} \quad (11)$$

Where $V_q^{(1)} = I_q^s / (Y_{in}(\omega_q) + g_1)$. From (7) the current source $i^{(2)}(t)$ is computed and then setting all current sources except $i^{(2)}(t)$ to be zero, one can obtain

$$v^{(2)}(t) = \sum_{q_1=-Q}^{+Q} \sum_{q_2=-Q}^{+Q} \frac{g_2 V_q^{(1)} V_q^{(2)}}{Y_{in}(\omega_{q_1} + \omega_{q_2}) + g_1} e^{j(\omega_{q_1} + \omega_{q_2})t} \quad (12)$$

Similarly from (8), the current source $i^{(3)}(t)$ and accordingly the third-order voltage caused by $i^{(3)}(t)$ is then given in (13).

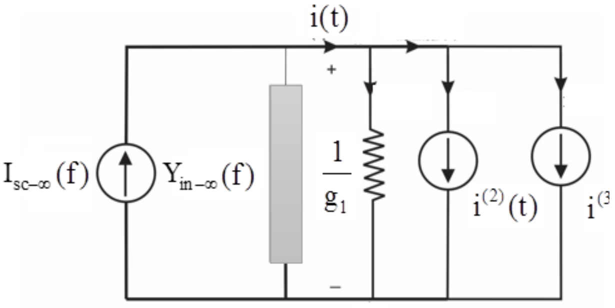


Figure (2) Equivalent circuit of figures 1(b) based on nonlinear currents method.

$$v^{(3)}(t) = 2g_2 \sum_{q_1=-Q}^{+Q}\sum_{q_2=-Q}^{+Q}\sum_{q_3=-Q}^{+Q} \frac{g_2 V^{(1)}_{q_1} V^{(2)}_{q_2} V^{(3)}_{q_3}}{Y_{in}(\omega_{q_2}+\omega_{q_3})+g_1} \times \frac{e^{j(\omega_{q1}+\omega_{q2}+\omega_{q3})t}}{Y_{in}(\omega_{q_1}+\omega_{q_2}+\omega_{q_3})+g_1} - g_3 \sum_{q_1=-Q}^{+Q}\sum_{q_2=-Q}^{+Q}\sum_{q_3=-Q}^{+Q} \frac{V^{(1)}_{q_1} V^{(2)}_{q_2} V^{(3)}_{q_3}}{Y_{in}(\omega_{q_1}+\omega_{q_2}+\omega_{q_3})+g_1} \times e^{j(\omega_{q1}+\omega_{q2}+\omega_{q3})t}$$

(13)

Finally, the total voltage response $v(t)$ can be found from (2), (11), (12), and (13). As seen in (11), (12), and (13), in despite of Volterra series [15], efficient closed-form solution for induced voltage at k-th order is easily computed without needing to compute the total responses.

Nonlinear Analysis

In this section, the proposed model is first applied to nonlinear antennas and its validity in comparison with harminic balance is investigated. The impact of incident angle on FSS performance of nonlinear antennas is then carried out and compared with Volterra series-based results in [15].

Validity

In this section, the proposed model is first applied to nonlinear antennas and its validity in comparison with harminic balance is investigated. The impact of incident angle on FSS performance of nonlinear antennas is then carried out and compared with Volterra series-based results in [15].

$$i = 1/75v + 4v^3 \qquad (14)$$

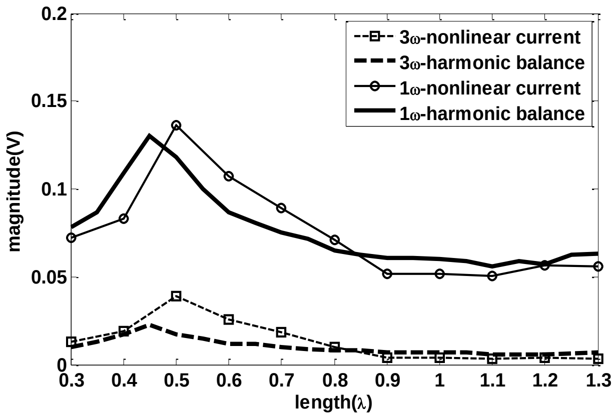


Figure (3) Magnitude of induced voltage of single nonlinear dipole at mixing harmonic frequencies computed by nonlinear current approach and harmonic balance technique.

The dipole is also normally illuminated by an incident plane wave of magnitude $E_i = 1V/m$. The induced voltage at three mixing harmonic frequencies are shown in figure 3. In the same figure, the HB results [6] are also shown. As can be seen, close agreement is achieved. Note that due to nonlinearilty of the load, the induced voltage at second order is zero (see (12) in previous section) and not shown in this figure.

is the same as the first example. The vertical and horizontal spacing between dipoles are the same. Figure 4 shows different mixing harmonics frequencies computed by the two

In the second example, an infinite array of nonlinear dipoles is considered. Each nonlinear dipole

methods. Good agreement is once more observed which demonstrates the accuracy of the modeling approach.

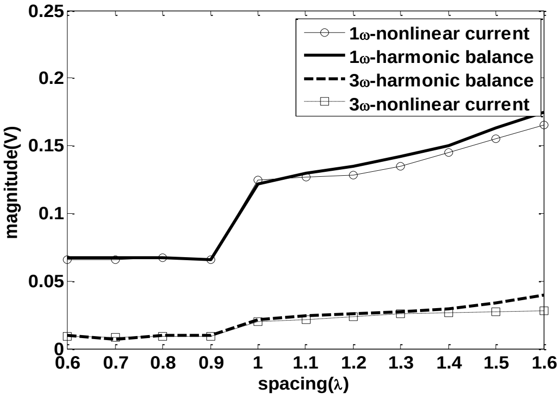


Figure (4) Magnitude of induced voltage of infinite array of nonlinear dipoles at mixing harmonic frequencies computed by nonlinear current approach and harmonic balance technique [6].

Phase Cojugation

As seen in figure 4, for normalized spacing less than 0.9, the voltage magnitude of third order is considerably decreased with respect to fundamental frequency. This property makes such structures benefit in time reversal applications where self-tracking of signals for transponder applications is required [16]. In [15], a complex hybrid method was proposed based on combining MoM and Volterra series and the effects of spacing among antennas and incident angle on the time reversal performance were investigated. In this article, to show the capability of the proposed model, these effects are investigated. To this end, the nonlinear dipole in previous sub-section is again used and the induced voltage for three values of incident angles, i.e. $\theta = 30,45,60^{\circ}$, are then computed and shown in figure 5. As seen, when the incident angle is decreased, the third-order component is approximately constant, but the fundamental component is decreased. This means that the time reversal property is suppressed which is in agreement with [15].

It should be note that the proposed model was validated for normal incidence in the previous section. It evidently results in better agreement with harmonic balance technique for oblique incidences, since the induced current due to plane wave on the wire surface is decreased.

Conclusions

In this study, the nonlinear currents-based approach was used to extract the effects of oblique incidence on the time reversal performance of nonlinear wires. Through the simulations, the key findings were achieved as following

1-In despite of Volterra series, the proposed model can easily extract different mixing components without needing to compute total response. Such property in design point of view is of importance.

2-The simulation results were validated with harmonic balance technique demonstrated the accuracy of the model.

3-Impact of incident angle on the time reversal performance was investigated which was in close agreement with Volterra series.

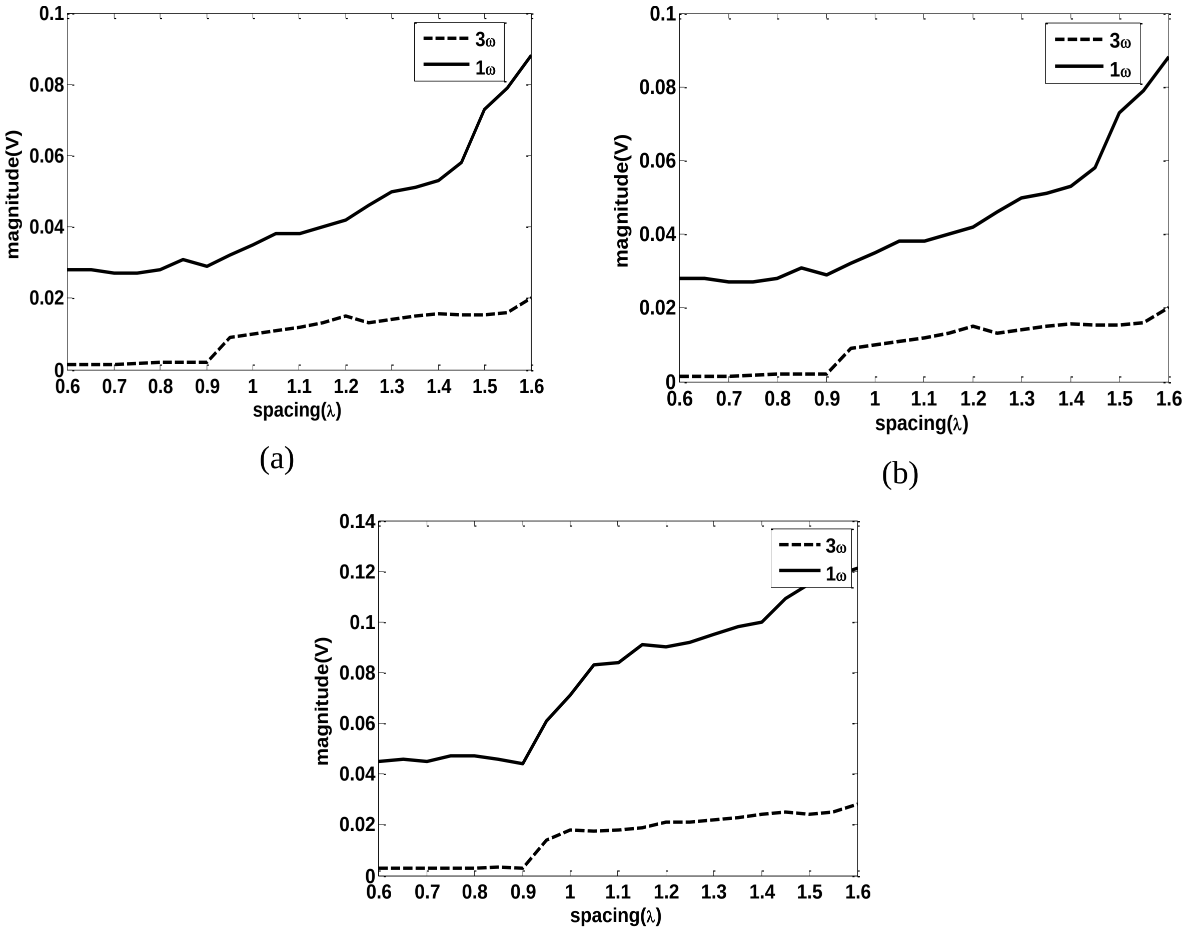


Figure (5) Spectral content across load under incidence of (a): $\theta = 30\,\deg$, (b): $\theta = 45\,\deg$, (c): $\theta = 60\,\deg$.

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