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BANDWIDTH ENHANCEMENT OF A CLASS OF CLOAKS INCORPORATING METAMATERIALS

M. Danaeifar*, **M. Kamyab, A. Jafargholi, and M. Veysi**

Department of Electrical Engineering, K. N. Toosi University of Technology, P. O. Box 16315-1355, Tehran, Iran

Abstract—A new method for increasing the bandwidth (BW) of a class of cloaks is presented. Simulation results reveal that the bandwidth of this class of cloaks is increased by embedding the two-dimensional transmission networks in a medium whose refractive index is smaller than unity. The low refractive index medium is realized by embedding several thin wires in a host medium. The overall bandwidth of the proposed cloak for reflectance less than -25 dB is revealed to be increased by more than 17% compared to its conventional counterpart.

1. INTRODUCTION

In recent years, the electromagnetic cloaking has attracted increasing attention in the electromagnetic community because it can provide the possibility of reduction of the object's scattering cross section (SCS) from electromagnetic wave impinging on the object [1, 2]. As the reflections from the cloaked object reduce, the cloak provides a better performance. As a result, reflections should be reduced to extremely small values, typically less than $-20/-25$ dB, depending on the application. To achieve cloaking, a variety of theoretical and numerical methods have been employed. The most widely used methods are the coordinate-transformation cloak [3–5]. However, this electromagnetic cloak, similar to the other electromagnetic cloaks, is narrow in bandwidth.

Recently, a novel method for realization of an electromagnetic cloak operating in the microwave region has been presented in [6–9]. This cloak is mainly based on the transmission line network.

In this method, the electromagnetic wave that impinges on the cloak structure is efficiently passed through the transmission-line

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* Corresponding author: Mohamad Danaeifar (danaeifar@ee.kntu.ac.ir).

networks. As a result, these cloaks just hide the objects which are small enough to fit inside space between the wire sections of the transmission-lines. This drawback severely limits its practical application.

To overcome this restriction, some modifications have been proposed. Moreover, this paper presents a novel technique for increasing the bandwidth of the transmission line based cloaks without sacrificing its performance. It has been demonstrated with several numerical investigations that embedding the transmission line network into a medium whose relative permittivity is smaller than unity provides a much wider bandwidth over which the reflectance is less than -25 dB. To this aim, an array of parallel wires has been used to realize an appropriate host medium in the simulations. As a result, compared to the conventional transmission line based cloaks, the cloak introduced in this paper seems to be more effective when a cloak with good performance and wide bandwidth is desired. The commercial software CST Microwave Studio is adopted for the simulations.

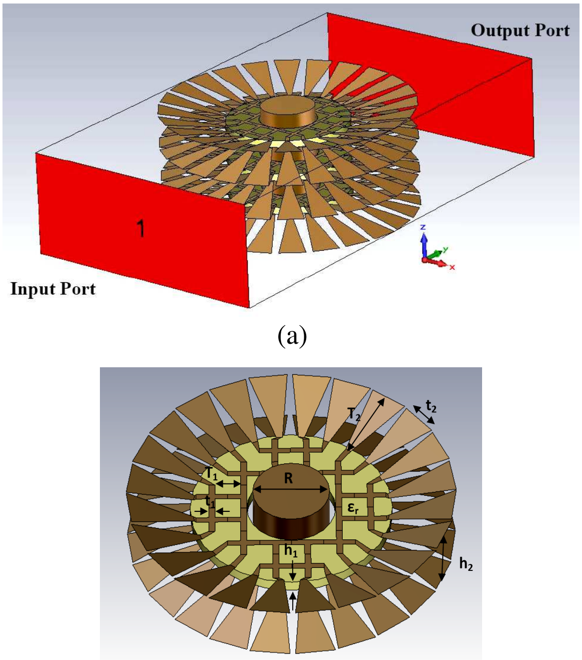
2. IMPROVED TRANSMISSION-LINE NETWORK CLOAK

Recently, a volumetric cylindrically shaped cloak composed of several two-dimensional networks that are stacked on top of each other has been proposed in [8, 9]. As it is mentioned before, these cloaks just hide the objects which are small enough to fit inside space between the wire sections of the transmission-lines.

However, further investigations reveal that the cloaked object placed at the center of the structure can cut the transmission-line network without affecting its performance. A schematic of the proposed transmission-line based cloak is shown in Figure 1. Material of the cloaked object and transmission-line are PEC[†]. As can be seen, the cloaked object is here a cylindrical box of diameter 12 mm. Other design parameters of the transmission-line cloak are also labeled in Figure 1(a). As a result, bigger objects can be concealed by the improved transmission-line cloak.

Here, the transmission-line based cloak is illuminated by the plane-wave in an effort to investigate its behavior as a function of frequency. Using CST simulator, the boundary conditions are determined such that a TEM plane wave (E_z and H_x) is considered and the x-y and y-z planes are considered as $E_t = 0$ and $H_t = 0$, respectively. When electromagnetic waves impinge the structure, S_{11} and S_{21} of these cloaked objects are calculated. This model of cloak and object with input and output ports are shown in Figure 1(b).

[†] Perfect Electric Conductor.



(a)

(b)

Figure 1. (a) CST model of cloak and object with input and output ports. (b) Schematic of the transmission line-based cloak: $R = 12\,\text{mm}$, $t_1 = 0.95\,\text{mm}$, $h_1 = 1.65\,\text{mm}$, $T_1 = 3.96\,\text{mm}$, $\varepsilon_r = 1$, $t_2 = 6.17\,\text{mm}$, $h_2 = 8.28\,\text{mm}$, $T_2 = 10.54\,\text{mm}$.

The simulated reflection coefficient for a transmission-line cloak as a function of the diameter of the cloaked object is shown in Figure 2. It can be seen from the figure that increasing the diameter of the cloaked object to above a certain threshold significantly limits the operating bandwidth of the cloak.

3. THE EFFECT OF PERMITTIVITY ON THE CLOAKING

The electromagnetic properties of a transmission line cloak are determined by its design parameters. Among these, the relative permittivity of the host medium plays an important role in determining the operating bandwidth of the cloak. When studying the effect of the relative permittivity on the operating bandwidth, other design parameters of the transmission line cloak are kept the same as

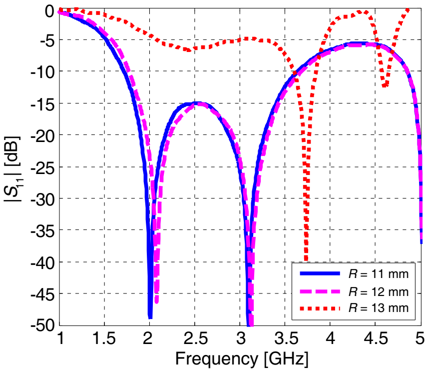


Figure 2. The simulated reflection coefficient for a transmission line based cloak as a function object's diameter.

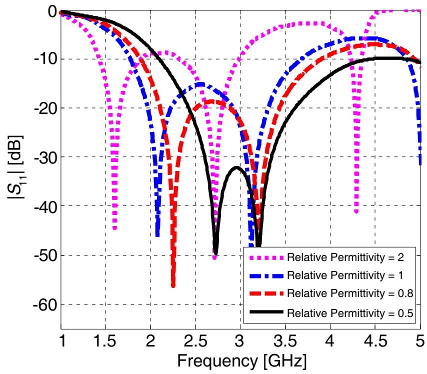


Figure 3. The effect of relative permittivity on the operating bandwidth of the transmission line based cloak.

in the caption of Figure 1. The simulated reflection coefficient for a transmission-line based cloak as a function of the relative permittivity of the host medium is shown in Figure 3. As can be seen, when the permittivity is decreased, the operating bandwidth of the cloak over which the reflection coefficient is less than -25 increases. However, the price we pay is the frequency shifting toward the higher frequencies. It was demonstrated in [10] that frequency dependence of the characteristic impedance of the transmission line based cloaks increases with increasing relative permittivity of the host medium. Thus, as the relative permittivity decreases, the characteristic impedance of the transmission line network as a function of frequency becomes more flat. The improvement in the operating frequency of the cloak can be mainly attributed to the flatness of the impedance of the transmission line network as a function of frequency.

4. PRACTICAL REALIZATION OF THE METAMATERIAL CLOAKING

It was revealed that decreasing the relative permittivity of the host medium can be led to an improved bandwidth. Thus, an array of parallel thin wires is employed to realize a low permittivity host medium. It is known that the magnitude of the relative permittivity of the thin wires is less unity at the frequencies around its plasma frequency. Figure 4 shows a transmission-line network based cloak loaded with an array of metallic thin wires. The array of thin wires

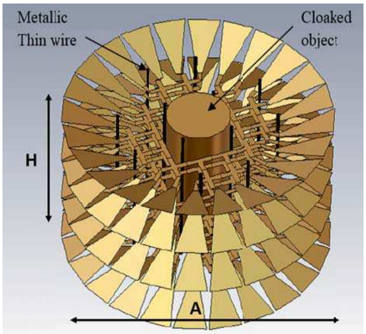


Figure 4. Schematic of a transmission line based cloak loaded with an array of metallic thin wires: $H = 24.84\,\text{mm}$, $A = 48.8\,\text{mm}$.

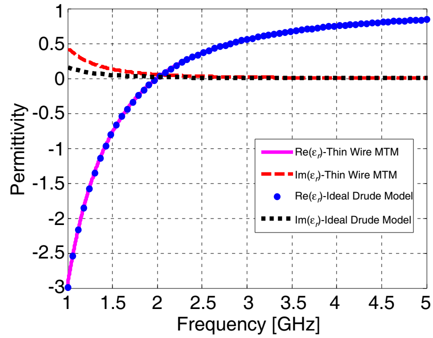


Figure 5. Retrieved effective permittivity of the thin-wire MTM cell. As a reference, effective permittivity of a Drude medium with the same retrieved effective permittivity of the thin-wire MTM is also plotted.

is designed separately (without the transmission line cloak) to have a plasma frequency of about 2 GHz. The total number of the thin wires is 12, and the separation distance between the wire elements is 10 mm.

Figure 5 shows the retrieved effective permittivity of the thin wire metamaterial. As can be seen, the thin wire metamaterial cell has permittivity that exhibit Drude behavior. Figure 6 shows a comparison between the simulated reflection coefficients for the transmission line-based cloaks with and without thin wires.

In the case of the conventional cloak, a narrowband deep null is observed in the reflection coefficient curve. While, in the case of the proposed cloak, two deep nulls appear very close to each other, which in turn result in an improved 25 dB-operating bandwidth (where $|S_{11}| < -25\,\text{dB}$). For comparison purposes, a modified transmission line based cloak embedded in a host medium with the same retrieved effective parameters of the thin wire loaded material (see Figure 5) is also simulated. As can be seen from Figure 6, the reflection coefficient of the transmission line based cloak embedded in the ideal metamaterial medium correlates nicely to that obtained for the transmission line based cloak surrounded by the thin wires. The difference between the thin-wire loaded and ideal Drude model cloaks can be attributed to the finite number of the thin wires and also to the coupling interactions between the thin wires and the cloak structure. The operating bandwidth of the transmission line-based cloaks with and

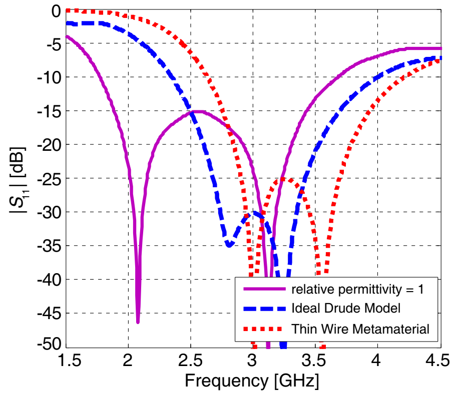


Figure 6. Simulated reflection coefficients for the proposed transmission line based cloak with comparison to a conventional transmission line based cloak. As a reference a transmission line based cloak loaded with an ideal Drude model (with the same retrieved effective parameters of the thin wire loaded material) is also simulated.

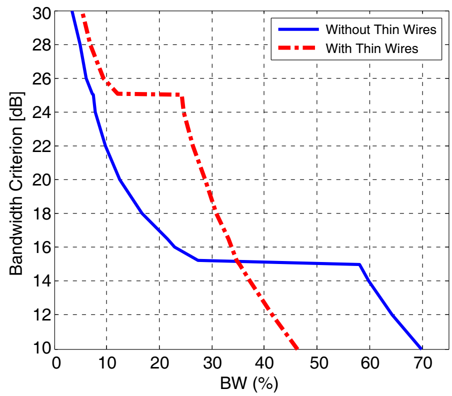


Figure 7. The operating bandwidth of the transmission line-based cloaks with and without thin wires as a function of the X-dB bandwidth criterion (where $|S_{11}| < -X$ dB).

without thin wires as a function of the X-dB bandwidth criterion (where $|S_{11}| < -X$ dB) is shown in Figure 7.

As can be seen, when the cloak performance is increased, the cloak bandwidth decreases, and vice versa. For the perfect cloak criterion (typically X larger than 40), both cloaks have very narrow bandwidths which jeopardize their practicality. While, for the imperfect cloak criterion (typically X less than 10), the cloak bandwidths are significantly increased. In either case, the conventional transmission line based cloak without thin wires has a wider bandwidth than that with thin wire metamaterials. However, the best design is a trade-off between the cloak bandwidth and cloak performance. The main application of the transmission line based cloak loaded with thin wire metamaterials is the situation where it is preferable to trade-off cloak performance for wider cloak bandwidth. For example, such a cloak will be most appropriate when a cloak with good performance (not perfect) and wide bandwidth is being required. In the case at hand, the 25 dB operating bandwidth of the cloak seems to be the right choice, which not only guarantees the good cloak performance but also provides wideband cloak. The 25 dB operating bandwidth of the proposed cloak is about 24.24% (ranging from 2.9 GHz to 3.7 GHz, see Figure 6). As a result, a 17% wider bandwidth is achieved as compared to the conventional transmission line based cloak.

5. CONCLUSION

A novel method for bandwidth enhancement of the transmission-line based cloaks is proposed. Numerical investigations reveal that embedding transmission line network in a host medium with a relative permittivity smaller than unity enhances the operating bandwidth of the transmission line based cloaks. Finally, an array of parallel wires is inserted into the host medium to practically realize the proposed approach. Although, this method provides the way to resolve the size limitation of cloaked object, some trade off needs to be considered; especially operational bandwidth and quality of cloaking.

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