Sinusoidally Modulated Reactance Surface Loaded Leaky Coaxial Cable

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***Abstract*—In this paper, the theory of sinusoidally modulated reactance surface (SMRS) is employed to enhance the radiation efficiency of leaky coaxial cable (LCX). The LCX's slots are loaded by a periodically etched dielectric stripe, partially converting the bounded monofilar mode into a radiating mode. The simulated results are discussed and it is shown that the coupling loss can be significantly decreased by SMRS loading, which increases the indoor coverage capability of the LCX.**

***Index Terms*—coupling loss, indoor wireless systems, leaky coaxial cable, sinusoidally modulated reactance surface.**

I. INTRODUCTION

There is a growing academic and commercial interest in exploiting the role of a leaky coaxial cable (LCX) in indoor communication systems. It is used as a base station antenna to improve the indoor coverage. Along with the single LCX as an access node antenna, multiple-input-multiple-output (MIMO) radio access deployments are also studied [1] [2]. The potential advantage is a simpler installation as the LCX is dual-purpose, functioning both as antenna and cable simultaneously. Mines and tunnels, the most common application sites of the LCX, generally have a uniform cross sectional area but offices and malls present a mix of corridors, halls and rooms. As the LCX uniformly radiates along its whole length, it is difficult to cover an entire indoor space with different spatial properties using the same LCX.

In this paper, a novel solution is presented to rationally increase the radiation efficiency of a coupled mode LCX by loading it with a surface incorporating periodically modulated reactance. Modulated reactance is obtained by conforming an etched dielectric stripe over the slots of the LCX, as shown later in this paper. The gap between the etched copper patches is varied periodically to obtain the desired variation of the reactance.

II. THEORETICAL BACKGROUND

A. Leaky Coaxial Cable (LCX)

A leaky coaxial cable is a modified form of an ordinary coaxial cable with judiciously made holes or slots along its outer conductor, as shown in Fig. 1. These slots leak the energy of the propagating guided wave over the entire length of the cable. Leaky coaxial cables may be categorized in two types, coupled mode and radiating mode, depending on the slots' shape and spacing. There are two distinct modes supported by a coupled mode LCX, named as monofilar and bifilar. The bifilar mode is mainly concentrated between the center and outer conductor of the coaxial cable while some of the energy leaks outside from the slots. This is generally utilized for communication purpose. In contrast, the monofilar mode is spread over the outer side of the outer conductor with some energy leaking back inside the cable [3]. By loading the cable with SMRS, the bounded monofilar mode is partially converted into a radiating mode.

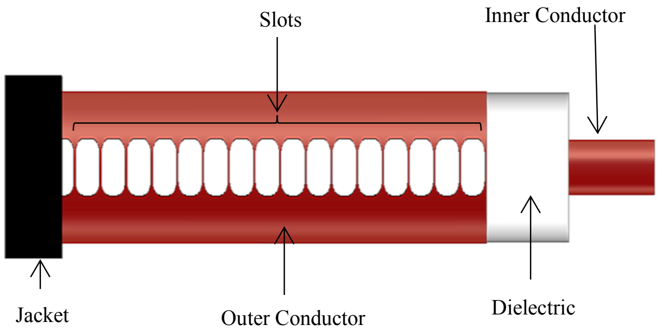


Fig. 1. Coupled mode leaky coaxial cable

B. Sinusoidally Modulated Reactance Surface (SMRS)

SMRS refers to any plane surface whose modal surface impedance is sinusoidally modulated. The propagation characteristics and relevance of the SMRS to a high gain modulated surface wave antenna was theoretically investigated by A. A. Oliner and A. Hessel [4]. They showed that, by periodically modulating the surface reactance above a threshold period, single or multiple discrete modes of the surface wave became propagating. In this way, power is radiated away from the surface wave. The surface impedance, η, of a SMRS in the xy-plane, with the direction of wave propagation assumed to be in z-direction, is given by following equation [4].

$$\eta(z) = j\eta_o X\left[1 + M\cos\left(\frac{2\pi z}{a}\right)\right] \qquad (1)$$

Where η_o is the free-space wave impedance, X is the average surface reactance normalized by the free-space wave impedance, M is the modulation factor and a is the periodicity of modulation. It is the parameters (X, M, a) which defines the characteristics of a SMRS.

Practical demonstrations have shown the applicability of the SMRS phenomenon in different applications such as leaky wave antenna, near field focusing and spoof plasmon wave radiation up to the THz range [5] [6] [7].

III. Design And Simulation Setup

In published literature, there are practical design variations of coupled mode LCX such as a continuous axial slot across the outer conductor or slots with a very small gap between them. The closely spaced slots are a good approximation of a continuous slot as long as the distance between the slots is very small relative to the wavelength. Here, a LCX with closely spaced slots is selected for the design.

First, a coupled mode LCX was designed and simulated. The cable diameter should not exceed a limit that allows the propagation of higher order modes at the maximum required frequency. Also, the selected dielectric material between the conductors should be of low dielectric constant. To reduce the complexity of the simulation model, the outer cable jacket was disregarded. It is usually made of low dielectric constant material and does not noticeably influence the electrical performance of the cable. The selected frequency range was from 100 MHz to 2.5 GHz, covering the majority of commercial communication bands having LCX applications. A total length of 830 mm was simulated, excited by a waveguide port. There were 44 mm of normal coaxial cable sections at both of the ends. The inner and outer conductor diameters of the coaxial line were 9.3 mm and 25.2 mm, respectively. The dielectric constant of the material between the conductors was chosen to be of 1.4.

In the second step, the LCX was loaded by a SMRS to enhance its radiation efficiency. There are three previously presented fundamental parameters, X, M and a, which dictate the performance of an SMRS. The average surface reactance, X, is an inherent property of any structure and it depends on the propagating mode. The modulation factor, M, governs the leakage rate. The periodicity, a, is a wavelength dependent parameter and it usually lies between half to one wavelength.

Generally, the SMRS is designed with a target frequency and the direction of maximum radiation. In this case, it was not the goal to transform the LCX into a high gain directional antenna, although that is possible. It is only wanted to increase the radiation efficiency to a certain required level without compromising the propagation nature of the LCX.

Here, five periods of the modulated reactance dielectric stripe, conformed over the LCX were simulated. The width and length of the dielectric stripe was 12 mm and 800 mm respectively, sufficient to cover the LCX slots, and its thickness was 3 mm. The period length and the modulation factor were arbitrarily chosen and their effect was numerically studied. The dielectric constant of the stripe was parametrically studied and selected to be 11 for this work. At values lower than the selected value, the effect of loading was minimal and at higher values the dual nature of the LCX was transformed into that of a directional antenna. The numerical simulations were carried out by using the commercial CST Microwave Studio. The simulation model is shown in Fig. 2, the loaded LCX simulation model was

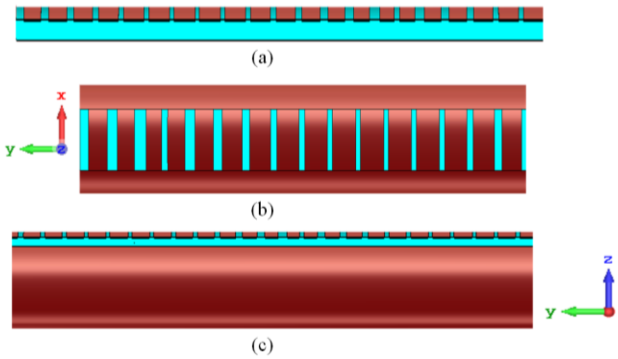


Fig. 2. Simulation model for SMRS loaded LCX (a) copper etched dielectric stripe (b) a single period of loaded cable, top view (c) LCX loaded with etched copper dielectric stripe, side view

excited with waveguide port from one end and terminated with 50 ohm load on the other side.

IV. Results And Discussion

The simulation results are presented in the form of a comparison between a LCX and a SMRS loaded LCX. It is observed in Fig. 3 that impedance matching did not disturb by the loading of the LCX. The S11 was below -30 dB at all frequencies, which shows good impedance matching. To observe the impact of LCX loading, the 2D electric field strength plots at 2.4 GHz are mapped in Fig. 4. The cables were vertically bisected from the top, showing the half-section in the yz-plane. In both cases, the field confined between the conductors was strongest, depicting the bifilar mode. It shows that the propagation characteristics of the LCX were not significantly changed by the SMRS loading. In the periphery, it is visible that the field strength was significantly higher in the loaded case. Also there were directional contours in the loaded case, relating it to the SMRS phenomenon.

In addition to standard antenna performance indicators, an LCX is judged by its coupling loss value. This is defined as,

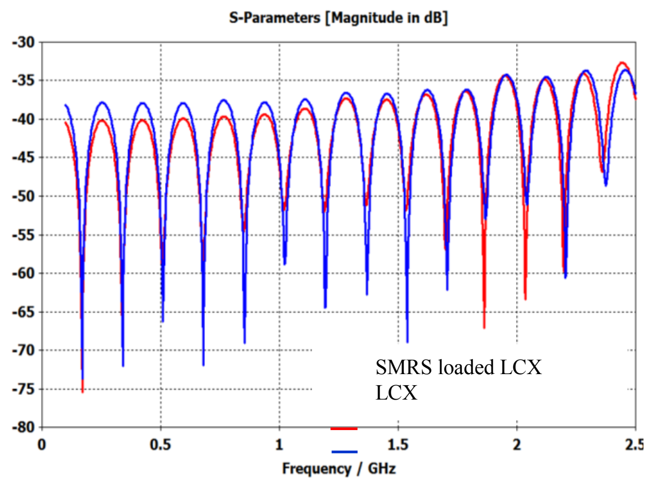
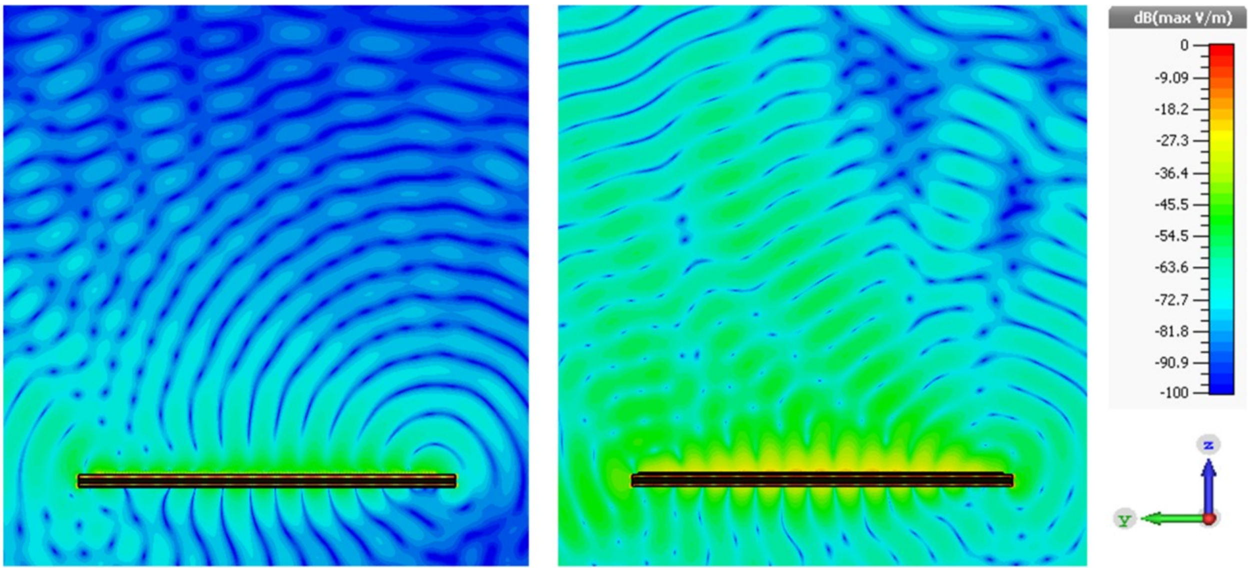


Fig. 3. Comparison of S11, the impedance matching of the studied cable structures



(a) (b)

Fig. 4. 2D plot of electric field strength around the cable at 2.4 GHz (a) LCX (b) SMRS loaded LCX

$$\text{Coupling Loss (dB)} = -10\log\left(\frac{P_r}{P_t}\right) \qquad (2)$$

where P_r is the received power by the standard half-wavelength dipole antenna and P_t is the input power. The P_r was calculated by the recorded electric field strength, *E*, utilizing the empirical relation, $0.13\ \lambda^2|E|/120\pi$ [8] , and Pt was set to 0.5 watt. Fig 5 depicts the decrement in coupling loss resulting from loading the LCX with SMRS. The electric field was recorded at a distance of 1 m from the center of the cable in both cases by placing an electric field probe in the simulation model and calculating the coupling loss utilizing (2). Apart from the 230 MHz to 500 MHz band there was a significant 5-10 dB improvement in the coupling loss. As the wavelength decreased, it became more comparable to the chosen period length, *a,* of the design. This caused an improved coupling loss performance at the higher frequencies. According to the literature and the commercial data sheets, far field radiation patterns are usually neglected in the context of an LCX.

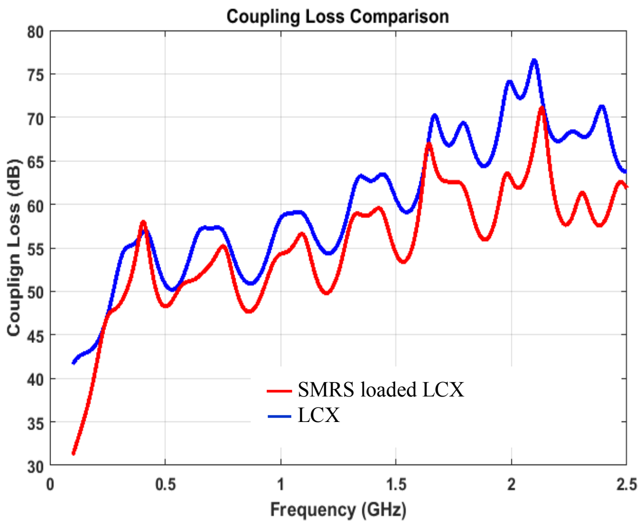


Fig. 5. Coupling loss vs frequency at 1m distance from the cable center

V. Conclusion

In this communication, a solution is presented to decrease the coupling loss of an LCX by loading it with a SMRS. It has been shown that coupling loss can be decreased over a wide band of frequencies by the judicious selection of SMRS properties. In normal LCX deployment there are places such as corners where the signal strength is insufficient. SMRS loading may be utilized to increase the signal strength in such places. In general, the solution may find its utility in distributed antenna systems (DAS) and indoor communication systems. We conclude that SMRS loading complements the LCX performance.

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