SOLENOID ABOVE GROUND PLANE - EQUIVALENT CIRCUIT

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Abstract

Wide-band vector measurements of transmission structures formed by solenoids with 2, 4 and 6 turns above ground plane were performed in the frequency band 45 MHz – 18 GHz. Novel equivalent circuits of these structures were designed. The equivalent circuits fit the measured data very well in the frequency band DC – 11 GHz. Comparison with models known up to now are given.

Keywords

Solenoid above ground plane, equivalent circuit, microwave measurement

1. Introduction

A simple single-layer solenoid is a frequently used component not only on frequencies of hundred of MHz, but also in microwave and milimetrewave bands namely in bias circuits. This component is mostly mounted in vicinity of the ground plane. Surprisingly, ground proximity is not taken into account in commonly used formulae for solenoid parameters calculations, see [1]. Moreover there is no model, as far as the authors know, describing behaviour and nature of this structure.

Rhea [2] suggests a simple model but it agrees with measurement only on low frequencies where the length of the solenoid is small concerning the wavelength.

The purpose of this paper is to present frequency wide-band experimental data for 2, 4 and 6-turn solenoids placed above ground plane to give better understanding of the nature of the structure, to test available expressions, and to design a new equivalent circuit approximating behaviour of the structure.

2. Measurement

Simple test fixtures with SMA connectors for precise vector measurements of the solenoid above the ground plane were prepared. These test fixtures give the possibility for correct vector calibration and de-embedding of all parts except the solenoid. Fig. 1 shows the arrangement for the 4-turn solenoid.

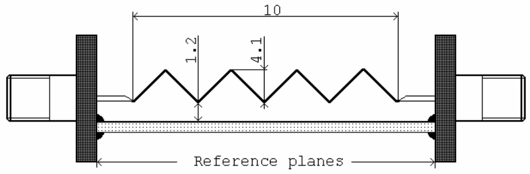

Fig. 1 Test fixture for the measurement of the solenoids with 4-turn solenoid inserted. Dimensions in mm.

2, 4, and 6-turn solenoids with inner diameter of 4.1 mm and the diameter of the wire 0.3-mm were prepared and soldered into the test fixtures. The calibration was performed in the reference planes on the flanges of the connectors. The measurements were performed on HP 8410 vector network analyzer with HP 8410-PC Controlling System applied [3], in wide frequency band from 45 MHz to 18 GHz.

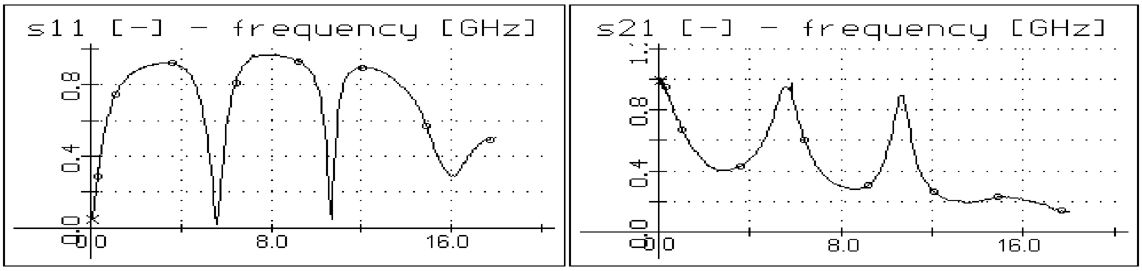

Fig. 2 Measured and de-embedded data of 2 turns solenoid.

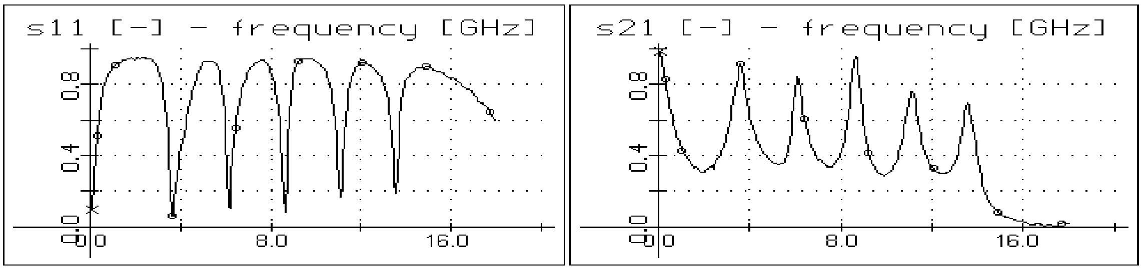

Fig. 3 Measured and de-embedded data of 4-turn solenoid

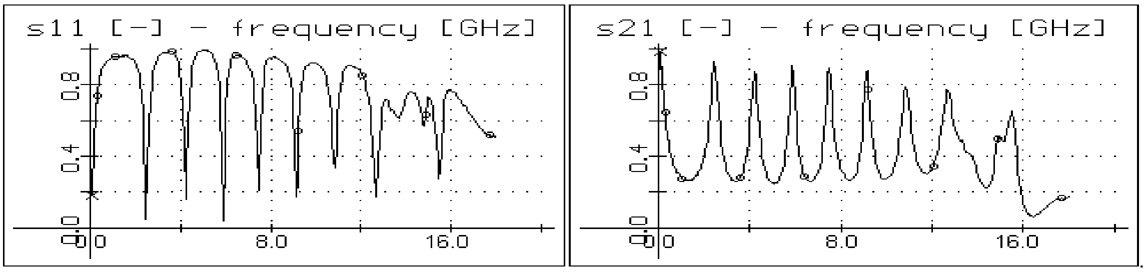

Fig. 4 Measured and de-embedded data of 6-turn solenoid

After de-embedding the transmission lines formed by the inner conductor of the connectors and the ground plane by MIDE [4] the data corresponding to the only solenoid above the ground plane were obtained. Fig. 2, 3 and 4 show the measured and de-embedded data for the solenoids with 2, 4 and 6 turns.

3. Modeling

Several known models were tested with respect to measured data. First *the classic model* of the solenoid was used. It consists of an equivalent circuit shown in Fig. 5.

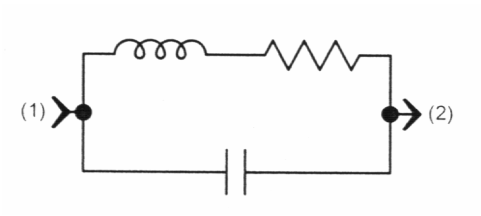

Fig. 5 Classic model of the solenoid.

Values of $C = 1$ pF, $L = 8$ nH and $R = 0.5\ \Omega$ were used for the modelling. Fig. 6 shows the results. It can be seen that this model does not correspond to the measured reality at all. This notices also Rhea, [2].

Then *Rhea's model* [2] was also tested. It consists of an ideal loss-less transmission line. The inductance and the capacitance of the line are determined by the low frequency inductance of the solenoid and capacitance between a cylinder with the same diameter and length as the solenoid and the ground. The inter-turn capacitance is not taken into account. The capacitance needs a correction concerning the capacitance of the ends of the cylinder. Then the impedance of the line is calculated. The method was applied on the 4-turn measured solenoid. Fig. 7 shows the results. Reasonable agreement between measured and calculated data is obtained only on low frequencies up to the first reflection minimum and the transmission maximum. On higher frequencies this model does not fit the measured data at all. Observing a significant disagreement between above-mentioned models and measurement results attention was given to physical interpretation of measured results at Figs.2, 3, 4.

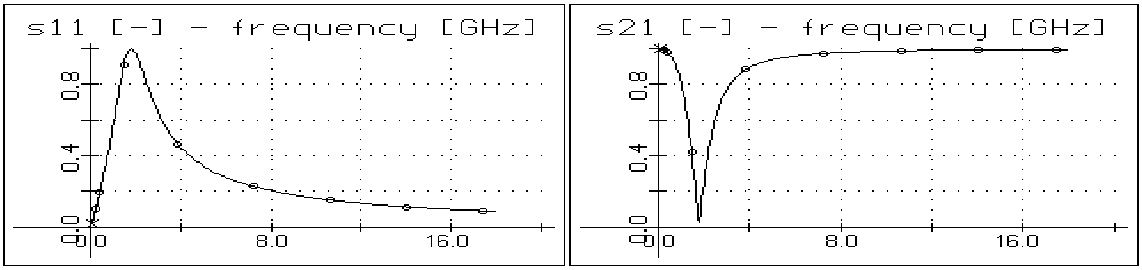

Fig. 6 Modeled s-parameters of the classic model.

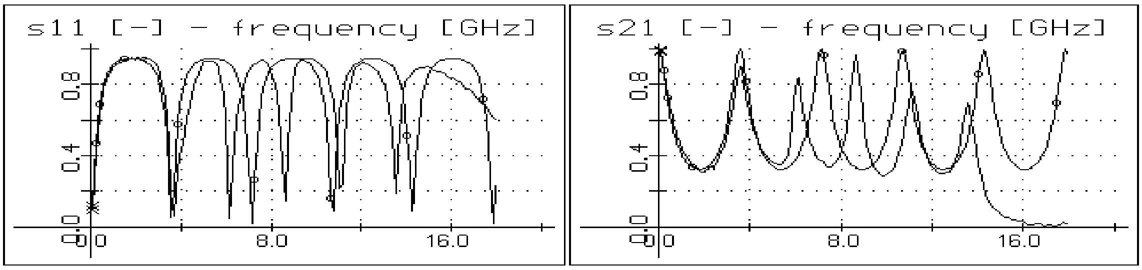

Fig. 7 Simulated s-parameters of Rhea's model for the 4-turn solenoid (oooo) vs. measured data.

It can be seen that the structures have, starting from low frequencies, a similar behaviour like a piece of an unmatched line. On the contrary to a piece of a homogeneous unmatched line the frequencies of reflection minima and transmission maxima do not repeat regularly with increasing frequency. Moreover approaching the upper frequencies the nature of structures changes rapidly suppressing the transmissions with relatively non-extreme corresponding reflection. Strong radiation of the structure was observed on these frequencies. Another phenomenon can be observed with respect to the number of turns. The frequency difference between the reflection minima and the transmission maxima decrease with greater number of turns. To approach to these properties a new structure of the equivalent circuit for the solenoid above ground plane was designed.

The New Model- the equivalent circuit comes from the line concept similarly like Rhea's model [2]. However the solenoid is considered as a large structure with respect to the wavelength. The equivalent circuit is composed of pieces of a homogeneous line with a high impedance *Zh* corresponding to the upper half turns of the solenoid and of pieces of a homogeneous line with a low impedance *Zl* corresponding to the lower half turns of the solenoid. Both lines have physical length *Pl.* The structure is ended by 2-quarter turns with low impedance *Zl.* Moreover the pieces are connected to each other with the capacitors *C* to represent the inter-turns capacitance. Fig. 8. shows the structure valid for the 4-turn solenoid. Corresponding structures were designed also for the 2-turn and 6-turn solenoids.

The structure can have dispersive properties. The lengths of the lines *Pl*, their impedances *Zh, Zl* and the inter-turn capacitances *C* were optimised with respect to measured data by MIDE. Curve fitting technique was applied. Figs. 9, 10 and 11 show the results.

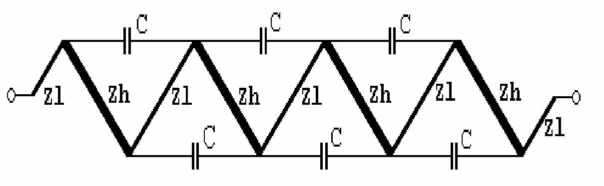

Fig. 8 Equivalent circuit of the new model for the 4-turn solenoid.

Good agreement between measured and modeled data in frequency band DC to 11 GHz can be observed. In this frequency band electrical lengths of the half turns between the capacitors were smaller than a quarter-wavelength. On frequencies above 11 GHz the behavior of the solenoid structure changes. The structure begins to radiate and the model is not further valid.

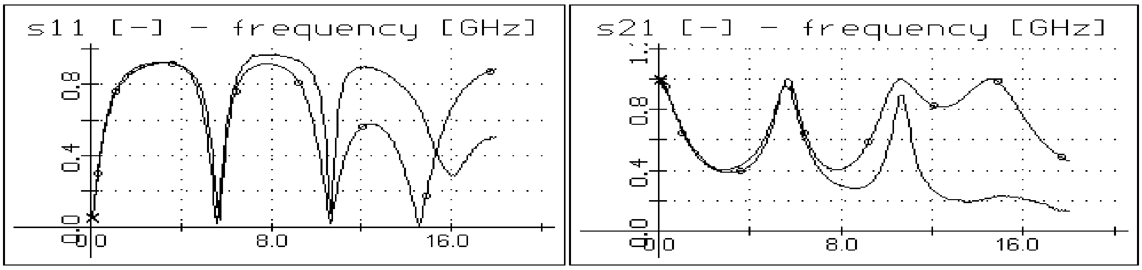

Fig. 9 Measured and simulated (oooo) s-parameters of the 2-turn solenoid. *Zh*=270 ohm, *Zl*=200 ohm, *Pl*=6.2 mm, *C*=0.025 pF.

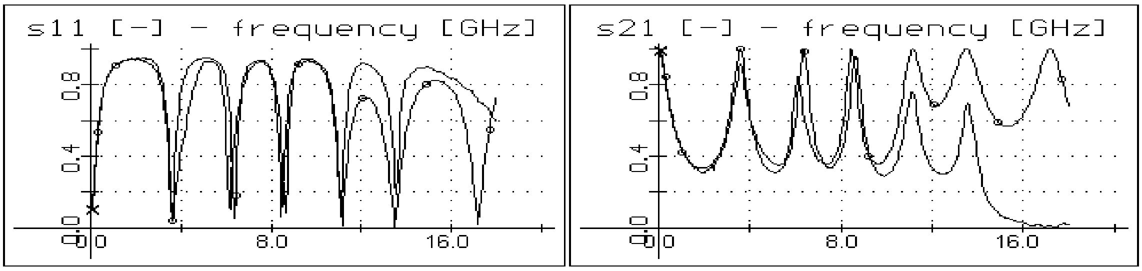

Fig. 10 Measured and simulated (oooo) s-parameters of the 4-turn solenoid. *Zh*=300 ohm, *Zl*=270 ohm, *P*l=5 mm, *C*=0.018 pF.

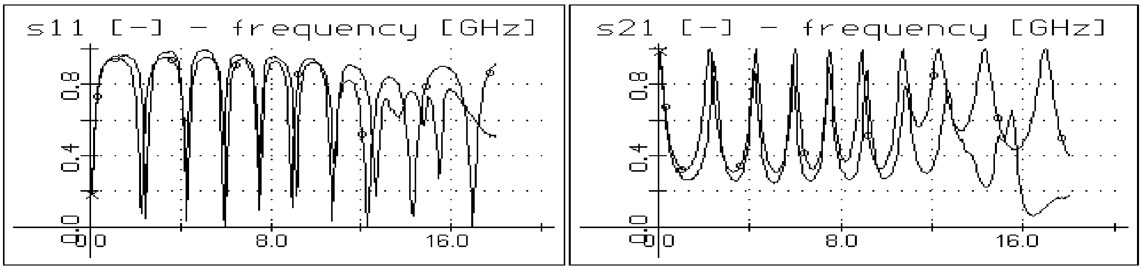

Fig. 11 Measured and simulated (oooo) s-parameters of the 6-turn solenoid. *Zh*=310 ohm, *Zl*=290 ohm, *Pl*=5.5 mm, *C*=0.012 pF.

4. Conclusion

Precise vector measurements of the 2, 4 and 6-turn solenoids above the ground plane were performed. The equivalent circuits known up to now were tested with respect to the measured data. Significant disagreement between modelled and measured data was observed. A new structure for the equivalent circuit of the solenoid above the ground plane was suggested and tested in the frequency band from 45 MHz up to 18 GHz. The new model is able to fit the measured data in the frequency band DC up to 11 GHz; it is below the frequency where the electrical length of the turns approaches half wavelength.

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About authors...

Karel HOFFMANN is active in the field of microwaves for over 25 years. He is with the Czech Technical University in Prague. His main interests include microwave measurements and circuit design. He has served as Joint MTT/AP/ED Chapter of Czechoslovakia Section IEEE Chairman.

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