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Medium frequency propagation characteristics of different transmission lines in an underground coal mine

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Abstract

A medium frequency (MF) communication system operating in an underground coal mine couples its signals to a long conductor, which acts as an MF transmission line (TL) in a tunnel to permit communications among transceivers along the line. The TL is generally the longest signal path for the system, and its propagation characteristics will have a major impact on the performance of the MF communication system. In this study, the propagation characteristics of three types of MF TLs in two layouts—on the roof and on the floor of a coal mine tunnel—were obtained in an effort to understand the propagation characteristics of different TLs in different locations. The study confirmed a low MF signal loss on all of these TLs. The study also found that the TLs in different layouts had substantially different propagation characteristics. The propagation characteristics of these different TLs in different layouts are presented in the paper.

Keywords

Attenuation measurement; phase measurement; propagation constant; propagation losses; transmission line measurement

I. Introduction

In an effort to support use of and research on medium frequency (MF) (300 kHz–3 MHz) communication systems in underground coal mines, we conducted experiments to obtain the MF propagation characteristics of three types of transmission line (TL) systems in two layouts in a coal mine tunnel. The conductors were either laid on the floor or hung from the roof. Three types of wire structures were used to construct these TL systems: a single-conductor wire, a twisted pair cable configured as a single-conductor line, and a TV twin lead also configured as a single-conductor line. The propagation parameters obtained on each of these TLs were characteristic impedance $Z_0(f)$, propagation constant $\gamma(f) = \alpha(f) + j\beta(f)$—where f is frequency, $\alpha(f)$ the attenuation constant, and $\beta(f)$ the phase constant, the power loss rate, and velocity factor. Although the measurement data confirmed an overall low propagation attenuation in all cases, the propagation characteristics of the TLs in

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different layouts were substantially different. The propagation characteristics of these TL systems are presented in this paper followed by a brief discussion.

I.1. MF Communication System

A MF communication system for underground coal mines is generally considered a parasitic communication system. The electromagnetic signals of a transmitter couple to existing nearby conductors commonly found in a coal mine tunnel such as a power cable or trolley wire. The conductors guide the signals, possibly propagating many kilometers, to reach to a distant receiver near the conductor. MF communication systems are attractive to the mining industry because they do not necessarily require a dedicated mine infrastructure, do not have extensive installation requirements, and, hence, should have a low initial cost. It is also anticipated that certain existing conductors in a mine—a continuous miner cable, for example—may have a higher probability to survive a disastrous accident than the dedicated active devices of other typical communication systems. For these reasons, MF communication systems are considered a good backup to more conventional systems such as leaky feeder and node-based systems.

I.2. MF Communication System Research

Mine MF communication systems have been investigated since the 1970s [1]–[7]. Very recent literature on modeling work and simulated MF propagation parameters on tunnel TL systems can be found in [8]. Measurements of current along a long conductor and current simulations confirmed a low signal attenuation along a TL hung within a coal tunnel [1], [2]. However, signal attenuation and other propagation characteristics along different TL systems in different layouts are seldom found on a comparable basis in the literature. A lack of measured propagation parameters $Z_0(f)$ and $\gamma(f)$ in previous studies also made it difficult for a general evaluation of the propagation characteristics of a tunnel TL and the factors that impact the propagation characteristics.

We have recently developed a method that was able to obtain all of the MF propagation parameters in a tunnel TL [9]–[11]. As indicated in the general voltage and current distribution functions (1) and (2) for a TL, the $Z_0(f)$ and $\gamma(f)$ are the basic parameters often needed for an analysis of signal propagation characteristics along the TL. In (1) and (2), V_0^+ denotes the incident sinusoidal voltage source, V_0^- the reflected voltage at the end of the line of length l, and x the distance from the incident voltage source.

The developed method is based on considering a longitudinal conductor in a long tunnel as a coaxial cable. The conductor, similarly to the center conductor of the coaxial cable, carries a forward signal, and the surrounding coal and rock of the tunnel, similarly to the outer conductor of the coaxial cable, carries the return signal. To collect the return signal current, the measurement method requires the construction of an electrical interface to the tunnel. This can be done by inserting multiple bolts in the coal and rock surfaces around the tunnel at each end of the conductor.

In addition to $Z_0(f)$, $\alpha(f)$ and $\beta(f)$, the power loss rate, *Loss*(f), and velocity factor, *VF*, along a TL can also be obtained from the method.

Similar to derivations presented by others [12]–[15], the method derives the propagation parameters from an open line impedance measurement, $Z_{oc}(f)$, and shorted line impedance measurement, $Z_{sc}(f)$, of a TL system measured at its input end as shown in Fig. 1. The characteristic impedance, $Z_0(f)$, at a given frequency, *f*, can be obtained from (3), $\alpha(f)$, from (4) where *l* is the length of the line, and, *Loss*(*f*), from (5). With open and shorted line impedance measurements at different frequencies, the propagation phase constant, $\beta(f)$, can be obtained from (6), the signal velocity from (7), and the velocity factor, *VF*, from (8). $2\beta(f)l$ in (6) is the input phase angle for a given line length of *l*. The detailed description on how to obtain $2\beta(f)l$ can be found in [11]–[14].

As shown through (3)–(8), this method requires merely open and shorted line impedance measurements as function of frequency to produce a complete set of the signal propagation parameters for a tunnel TL with no need for any other variables such as conductivity, permittivity, and permeability of the conductor and surrounding in-situ coal and rock of the TL, which are generally difficult and costly to measure with different frequencies and locations in an underground tunnel. The Z_{oc}/Z_{sc} method is suitable for TLs using various conductors and in-situ coal and rock conditions, in tunnels of different lengths, sizes, and shapes, and allows us to make an evaluation of the influence of various factors on the MF signal propagation characteristics of the tunnel TLs. This information can be very useful for MF communications equipment manufacturers and users.

$$V(x)=V_0^+e^{-\gamma(f)x}+V_0^-e^{\gamma(f)x} \quad (1)$$

$$I(x)=\left(1/Z_0\right)\left(V_0^+e^{-\gamma x}-V_0^-e^{\gamma x}\right) \quad (2)$$

$$Z_0(f)=\sqrt{Z_{sc}(f)\cdot Z_{oc}(f)}(Ohms) \quad (3)$$

$$\alpha(f)=\frac{1}{2l}\left|\frac{1+\sqrt{\frac{Z_{sc}(f)}{Z_{oc}(f)}}}{1-\sqrt{\frac{Z_{sc}(f)}{Z_{oc}(f)}}}\right|\left(\frac{Nepers}{Unit\ length}\right) \quad (4)$$

$$Loss(f)=8.686\alpha(f)\left(\frac{dB}{Unit\ length}\right) \quad (5)$$

$$\beta\left(f=\frac{f_2+f_1}{2}\right)=\frac{\pi(f_2+f_1)}{2l(f_2-f_1)}\left(\frac{Rad}{Unit\ length}\right)$$
$$for f_2>f_1, where\ frequencies f_2 and f_1 are\ selected\ to\ make 2\beta(f_2)l-2\beta(f_1)l=2\pi \quad (6)$$

$$v_p=\frac{\pi(f_2+f_1)}{\beta}\left(\frac{meters}{s}\right) \quad (7)$$

$$VF=\frac{v_p}{3.0 \times 10^8}, \quad (8)$$

$$velocity\ of\ light=3.0 \times 10^8$$

Several types of conductor wires can be found in coal mine tunnels, such as trolley wires, AC power cables, and metal-cored lifeline, which can act as a single-conductor TL to carry MF signals. Trolley wire has one or two conductors hung closely to the roof. An AC power cable generally consists of several twisted conductors which are either hung from the roof or laid on the floor, and a lifeline generally consists of a single or two parallel conductors hung from the roof.

To understand the effect of different line conductor structures on the TL propagation characteristics, we measured several different single-conductor architectures—a single conductor (to establish a baseline), a twisted pair cable, and a TV twin lead—in a coal tunnel. The two terminals of each end of the twisted cable and TV twin lead were shorted to make them equivalent to a single conductor. The measurement results and the derived propagation characteristics of these TLs are presented next.

II. Measurement Condition

The measurements were obtained in a tunnel in an active coal mine (Rio Coalburg #2 Mine,) in West Virginia. The average cross-sectional dimensions of the tunnel are given in Fig. 2. The tunnel had high humidity with water droplets coming down from the roof in some locations. Some small pools of water could be found on the floor.

The single-conductor, twisted pair cable, and TV twin lead were installed (only one type at a time) and measured in two layouts, hanging from the roof and lying on the floor. The average distance between a wire and the roof was about 25 cm, and the average distance between a wire and the floor was 5 cm. All TLs were about 457.2 m long. The single-conductor wire was TEW/UL1015 14AWG RED. The twisted cable was Mine Telephone Wire AWG #14 from LRIS-TEC Wire Company. The TV twin lead was 20 AWG FORM TWIN LEAD.

The impedance measurement system introduced in [9]–[11] was used in the experiment. An Agilent E4980A LCR meter was used for the impedance measurements. A group of 8 stainless bolts 7.9 mm in diameter were drilled into the tunnel wall to a depth of 152.4 mm to form a ground grid electrical interface at each end of the line to facilitate the current collection for the line’s impedance measurements.

It is worth noting that it is difficult to obtain the precise values of the propagation parameters for a long tunnel TL, but we can closely approach to the true values for a given TL. Our previous tests have shown that the propagation parameters derived from the TL open and shorted impedance measurements have little variation with a grid electrical interface having more than 6 bolts or using bolts longer than 152.4 mm (The test results were published in [10].) This suggests that most of the current for the MF signal flows through and is distributed over the surface layer of the tunnel wall. In addition, our experiments with and without RF conductive cream applied to the contacting surface between bolt and bolt hole yielded no notable differences on the propagation parameters for a TL. These test results suggest that an 8-bolt grid interface without the help of any bolt contact medium is adequate for the experiment to produce the propagation parameters of the TL, in the MF band, with reasonable accuracy

III. Propagation of Characteristics of TL Systems

The open and shorted line impedances were measured from 300 kHz to 2 MHz with a step size of 1 kHz. Some measurements ended up at a lower frequency. A total of up to 3,400 measurements on both open and shorted line impedances were used to derive the propagation parameters as a function of frequency for each conductor configuration given the two different layouts in this study.

III.1. Coal and Rock Impedances

The in-situ coal and rock strata in the tunnel form a solid signal return path. We are interested in understanding the electrical characteristics of this return path, which could influence the MF signal propagation characteristics for the tunnel TL system. Thus, we measured the impedance of the coal and rock between groupings of bolts at both the coal and rock interfaces of the lines. Fig. 3 shows a representative sample from over 100 sets of the coal and rock impedance measurements. Fig. 3 suggests that the electrical properties of the coal and rock are frequency-dependent. We found that the measurements taken from different groups of bolts located in different points in the tunnel showed a similar impedance distribution pattern but with very different impedance values. The coal and rock in the lower portion or the floor of the tunnel consistently had substantially lower impedance than in the upper portion or the roof of the tunnel, and the difference could be up to a factor of 6, indicating a non-uniform distribution, or location dependence, of the electrical properties of the coal and rock in the tunnel.

III.2. Propagation Characteristics of Single-Conductor Wire TL

The plots of the magnitudes of the open and shorted line impedance measurements of the single-conductor wire TLs on both the roof and floor are given in Figs. 4 and 5, respectively. The characteristic impedances derived from the measurements are given in Fig. 6, and the attenuation constants in Fig. 7, with the equation for a linear fit of the data also given for each layout to serve as an empirical model. The power loss rates with a linear fit equation for each case are in Fig. 8.

The input phase distribution, $2\beta(f)l$, versus frequency is given in Figs 9 and 10 for the wire on the roof and floor, respectively. The input phase distribution manifested a clear periodic variation. An easily identifiable period of the input phase permits us to correctly determine a value for the phase constant, $\beta(f)$. The process of determining $\beta(f)$ begins with selecting pairs of frequencies, f_1 and f_2, that satisfy $2\beta_2(f_2)l-2\beta_1(f_1)l = 2\pi$ radians—exactly one period—starting from the lowest to the highest frequencies. Many hundreds of frequency pairs could be selected satisfying this condition, but only several are needed to cover the frequency band measured. Table I provides the pairs selected for the TL on both the roof and floor. Consequently, the phase constants were obtained from these selected frequencies and plotted in Fig. 11 with a linear fit to the data for each layout. The plots of the velocity factors are given in Fig. 12. The average velocity factor for the wire on the roof was 0.79, and 0.59 for the wire on the floor. As can be seen in Figs. 6–12, there is a considerable difference in propagation parameters of the conductor hanging from the roof and lying on the floor, indicating that the location of the conductor within the tunnel can significantly impact the propagation characteristics.

III.3. Propagation Characteristics of Twisted Cable TL

Similarly to the process described for the single-conductor wire TL, the open and shorted impedance measurements of the twisted cable configured as a single-conductor TL system on both the roof and the floor were obtained. The derived characteristic impedances, attenuation constants, power loss rates, phase constants, and velocity factors are presented in Figs. 13–17. The average velocity factor was 0.77 for the cable on the roof and 0.55 for the cable on the floor. Similar to the single-conductor wire, the propagation parameters for the twisted cable are substantially different between the roof and floor, but very similar to the single-conductor TL.

III.4. Propagation Characteristics of TV Twin Lead TL

The open and shorted impedance measurements of the TV twin lead configured as a single-conductor TL system on the roof and floor were obtained. The derived characteristic impedances, attenuation constants, power loss rates, phase constants, and the velocity factors are presented in Figs. 18–22. The average velocity factor was 0.76 for the lead on the roof and 0.54 for the lead on the floor. Similar to both the single-conductor wire and twisted cable TL systems, the TV twin lead propagation parameters were substantially different between the roof and floor, but all of the TLs—whether single-conductor, twisted pair, or TV twin lead configured as a single conductor—had similar propagation parameters when in the same environment.

IV. Discussion

The propagation parameters of the single-conductor wire, twisted cable, and TV twin lead obtained in this study manifest some basic propagation characteristics of a TL in a coal mine tunnel. Comparison of these TL systems based on their propagation parameters can yield information to aid in the understanding of a tunnel TL system.

To facilitate the comparison, we first present the propagation parameters for the roof TLs in Table II and the floor TLs in Table III at 0.5 MHz. Within each table there is little variation among the corresponding parameters, indicating that the detailed internal structure of the TL has only a minor influence on the propagation parameters. In contrast, an analysis of the data presented in Tables II and III shows that a 0.5-MHz signal propagating along a single-conductor wire TL on the floor suffers 62% higher dB losses in power loss rate than a single-conductor wire TL on the roof, and both the twisted cable and TV twin lead TLs suffer 74% higher dB losses with the conductor on the floor compared to the roof.

The fact of the higher signal loss to the floor TLs than that to the roof TLs suggests that the performance of a MF communication system would be dependent on location of the TL conductor inside a tunnel, and that the communication system can have a short coverage with its TL conductor close to the floor compared to that with the conductor near the roof. This also suggests that a higher system performance can be achieved by selecting a TL conductor hung from the roof, as a signal path, during the planning stage of the system installation.

Overall, the propagation parameters of the TLs on the roof, as shown in this study, are considerably different from their floor counterparts. The roof TLs have a higher characteristic impedance, substantially lower attenuation constant, phase constant, and power loss rate, and greater velocity factor than their floor counterparts. These differences are likely driven by the conductor line spacing from the roof versus the floor, suggesting that the location of the conductor within the tunnel can be one of the influential factors on the propagation parameters of the TLs.

In contrast to a coaxial cable, which is generally believed to possess a uniform distribution of electrical properties in its outer layer current return path, the fact that the measured impedance of the tunnel floor is, as shown in section 3.1, substantially lower than that of the roof suggests that the electrical properties of the coal and rock as a current return path of a tunnel TL are location-dependent. This raises the question as to whether the location-dependent electrical properties of a tunnel TL return path could further complicate the signal propagation of the TL in different locations in the tunnel. As illustrated in [16], the return current of a single-conductor tunnel TL system could be concentrated on the nearest surface of the tunnel walls. This suggests that the nearest surface can exert a greater influence on the propagation behavior of the TL than those farther from the conductor. The precise question following this experiment then is whether the difference of the electrical properties between the roof and floor is an additional contributing factor to the MF signal propagation difference between the roof and floor TLs. Seeking an answer to this question is part of our future research.

In contrast to a TL with a metal return path such as a coaxial cable, which generally has a constant characteristic impedance in a wide frequency range [17], the tunnel TLs with a rock and coal return path, as shown in this paper and in references [9]–[11], all have frequency-dependent characteristic impedances within even a narrow frequency band. As presented in section 3.1, the impedance of the tunnel coal and rock is also frequency-dependent. The question, therefore, is whether the electrical properties of the coal and rock are connected with the frequency-dependent characteristic impedance of the TLs. Research is ongoing in attempting to find an answer to this question.

The fact that the characteristic impedance Z_0 of the tunnel TLs varies with frequency suggests that Z_0 becomes among the variables to determine the performance of a tunnel MF communication system. As shown in (2), the current along a TL is inversely proportional to its characteristic impedance Z_0. With the other variables fixed, a high Z_0 could, therefore, result in a low current that, in turn, could lead to low system coverage and, hence, low performance of the MF communication system. To avoid significantly degrading the system performance due to the variation of Z_0, several selectable frequency carriers can be made available for a communication system to help users identify a frequency with a low Z_0 in a given tunnel environment.

The dimensions of a tunnel and moisture in a tunnel are among some of the factors in determining the propagation parameters of a tunnel TL. Future investigation will provide data that take us toward understanding the contribution of these individual factors to the propagation characteristics of a tunnel TL.

It is worth mentioning that the linear fit functions shown in the figures in this paper are valid principally within their defined frequency band. Therefore, attempting to make a prediction using any of these functions beyond their stated frequency band can result in a misleading conclusion. By their intrinsic nature, some of the TL parameters are nonlinearly dependent on frequency, and would appear in the plot as a curve rather than the straight line as shown in the figures for the attenuation constants and power loss rates in this paper. As such, a linear fit function generated in a frequency band different from that given in the previous section can be different from the ones shown in this paper.

V. TL Measurement Method Comparison

There are three major methods for tunnel TL measurements: the Z_{oc}/Z_{sc} method [9]–[11], electrical current measurement method [1], and simulation method [8]. As demonstrated in this paper, a complete set of the propagation parameters can be obtained for a tunnel TL from the Z_{oc}/Z_{sc} method while the signal attenuation is in fact the only parameter obtainable from the electrical current measurement method. The current measurement method requires manually taking current readings along the TL conductor at repeated distance intervals, and the process needs to be repeated at different frequencies. This is considered a time-consuming and unsafe task, requiring workers to travel in a tunnel to collect current readings at different locations along the conductor. On the contrary, a fast, safe and automatic data acquisition system can be used for the Z_{oc}/Z_{sc} method which allows the workers to remain at both ends of the TL.

Both the simulation and the Z_{oc}/Z_{sc} methods can yield a complete set of propagation parameters for a TL. The Z_{oc}/Z_{sc} method can produce accurate results for any given tunnel TL, as the Z_{oc}/Z_{sc} method always takes every existing factor of the TL into account. A tunnel TL simulation can, however, hardly do so as it often requires a tunnel model. It is quite difficult to determine the many well-defined tunnel parameters required for tunnel modeling. For instance, tunnel walls generally have irregular surfaces; the size and shape of the tunnel cross-section are not uniform along the tunnel's length; the electrical properties of the tunnel's surrounding media are neither transversally homogeneous nor longitudinally uniform [8]. Therefore, in order to obtain simple key conclusions, a simplified tunnel model is often used for a tunnel TL simulation [8]. In the simulation, the actual tunnel is replaced by an equivalent cylindrical one with the same cross-sectional area; the tunnel is considered to have a homogeneous and uniform surrounding medium characterized by an average permittivity and conductivity; the influence of the permittivity of the surrounding medium is neglected. With these simplifications, a tunnel TL model is generated, and so are the simulation results. Some of the simulation results as shown in [8] are close to the measurements from the Z_{oc}/Z_{sc} method, but some are different. For example, although the characteristic impedances, Z_0s, from the simulation are found to fall within the range of the Z_0s from the Z_{oc}/Z_{sc} method, they are confined in a very small variation range (5%) compared to those (exceeding 100%) from the Z_{oc}/Z_{sc} method within the MF band. This suggests that a simulated Z_0 can be largely different from its measured counterpart at some frequencies. The similar results of comparison can be found with the other parameters. Despite this limitation, simulation can be a tool to provide a quick TL solution, especially to understand the impact of a particular factor of a tunnel TL on the signal propagation. It is expected that the gaps between the measured and simulated propagation parameters of tunnel TLs will become smaller as more measured TL parameters become available for tunnel TL simulation.

VI. Summary

The MF propagation characteristics of three TLs in a coal mine tunnel were presented in this paper: a single-conductor wire, a twisted pair cable, and TV twin lead—the last two with the double conductors joined at each end. The TL propagation parameters were determined with the lines in two layouts: on the roof and on the floor. The measurements presented also included the sample impedance of the in-situ coal and rock in the tunnel. Although a low signal loss was confirmed for all of these TLs, the TLs suspended from the roof exhibited a substantially lower attenuation than those on the floor. Similarly, the other propagation parameters—attenuation constant, phase constant and velocity factor—differed between TLs on the floor and those suspended from the roof. The MF measurements can provide valuable insight into the performance of the TL systems and how these systems might be incorporated into an MF communication system.

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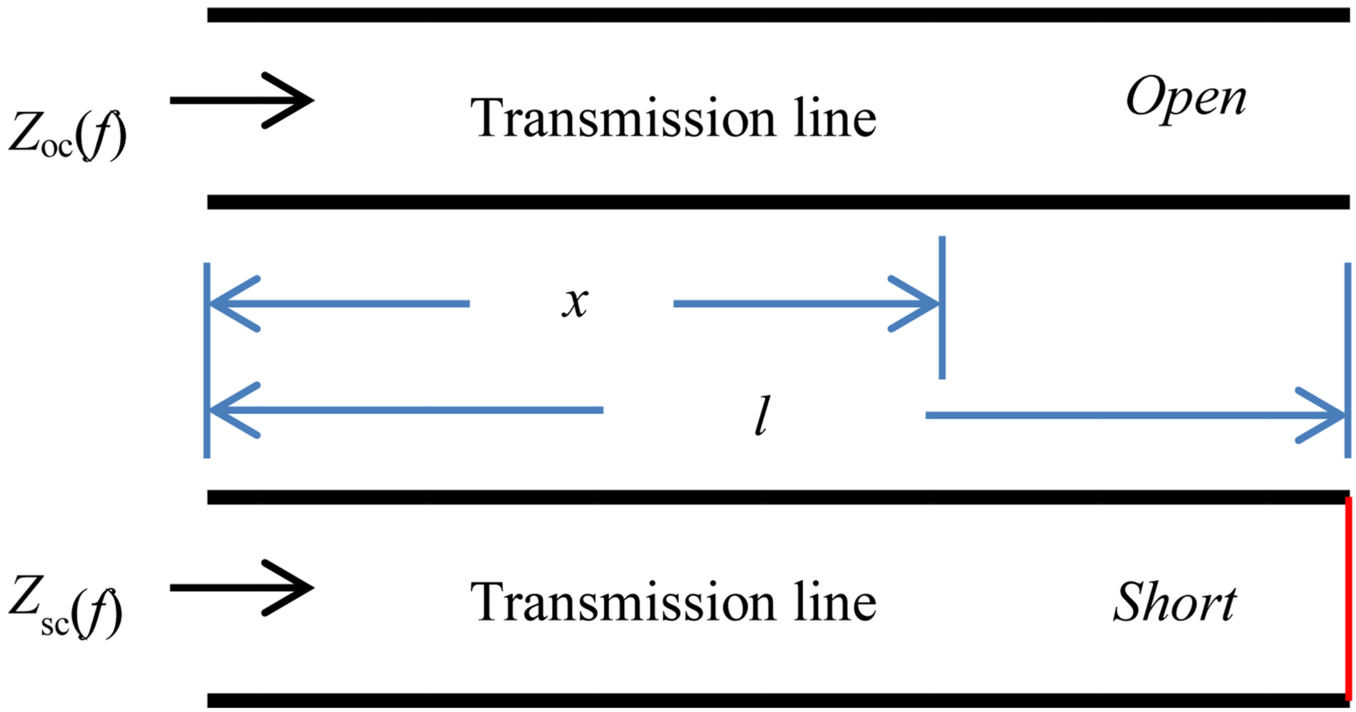

Fig. 1.
Open and shorted line impedances of a TL

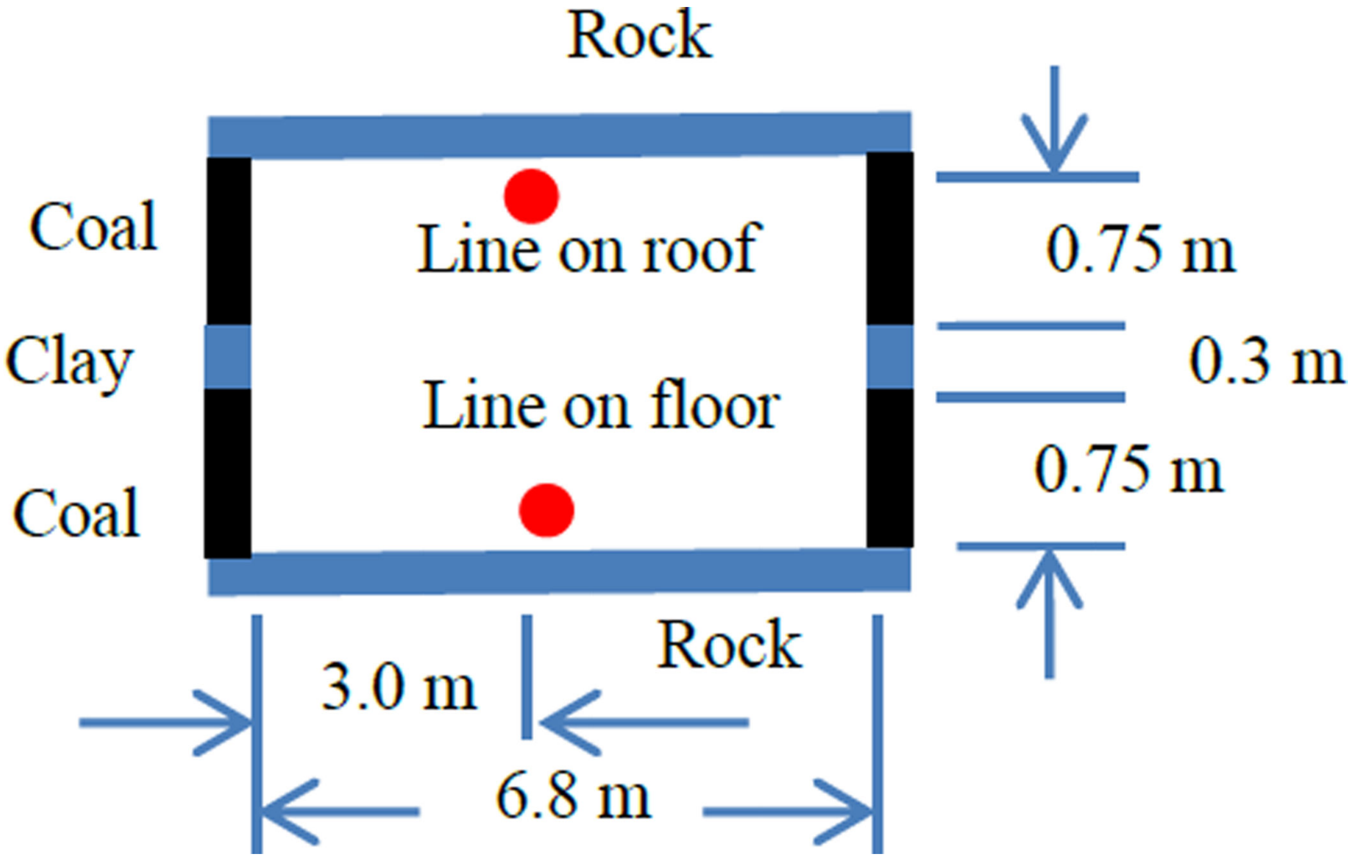

Fig. 2.
The average tunnel cross-sectional dimensions and the TL layouts (one layout configured and measured at a time)

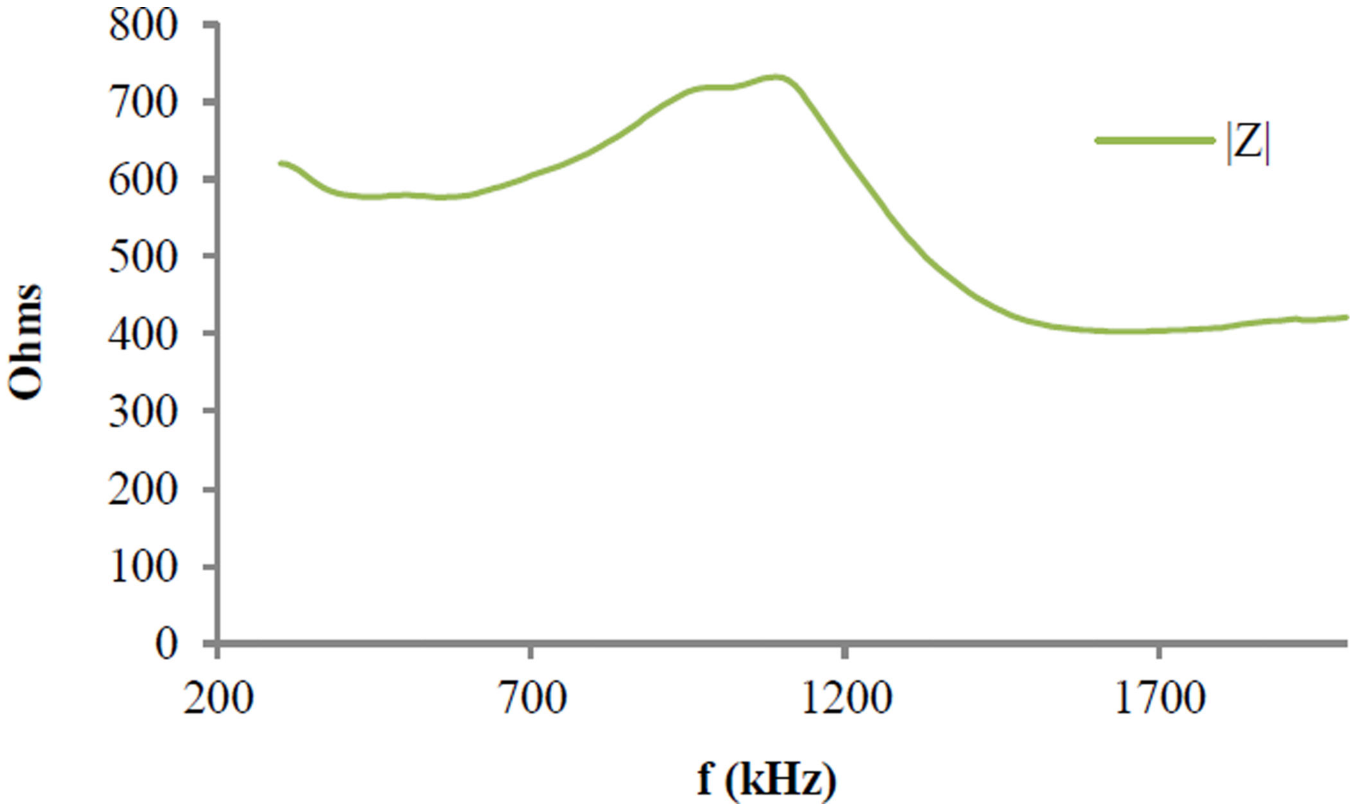

Fig. 3.
Impedance of the surrounding coal and rock of the tunnel

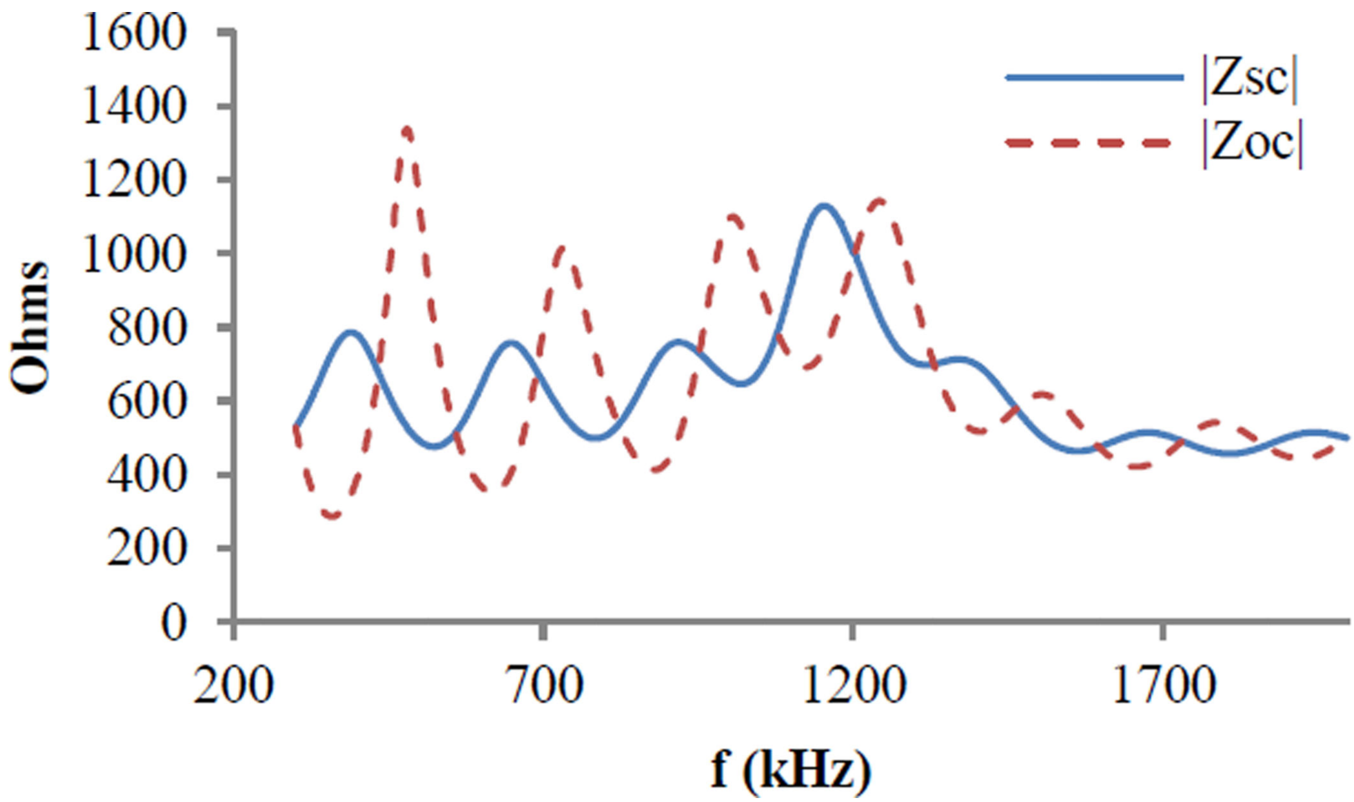

Fig. 4.

Open (dotted curve) and shorted (solid curve) line impedance measurements of the single-conductor wire TL near the roof

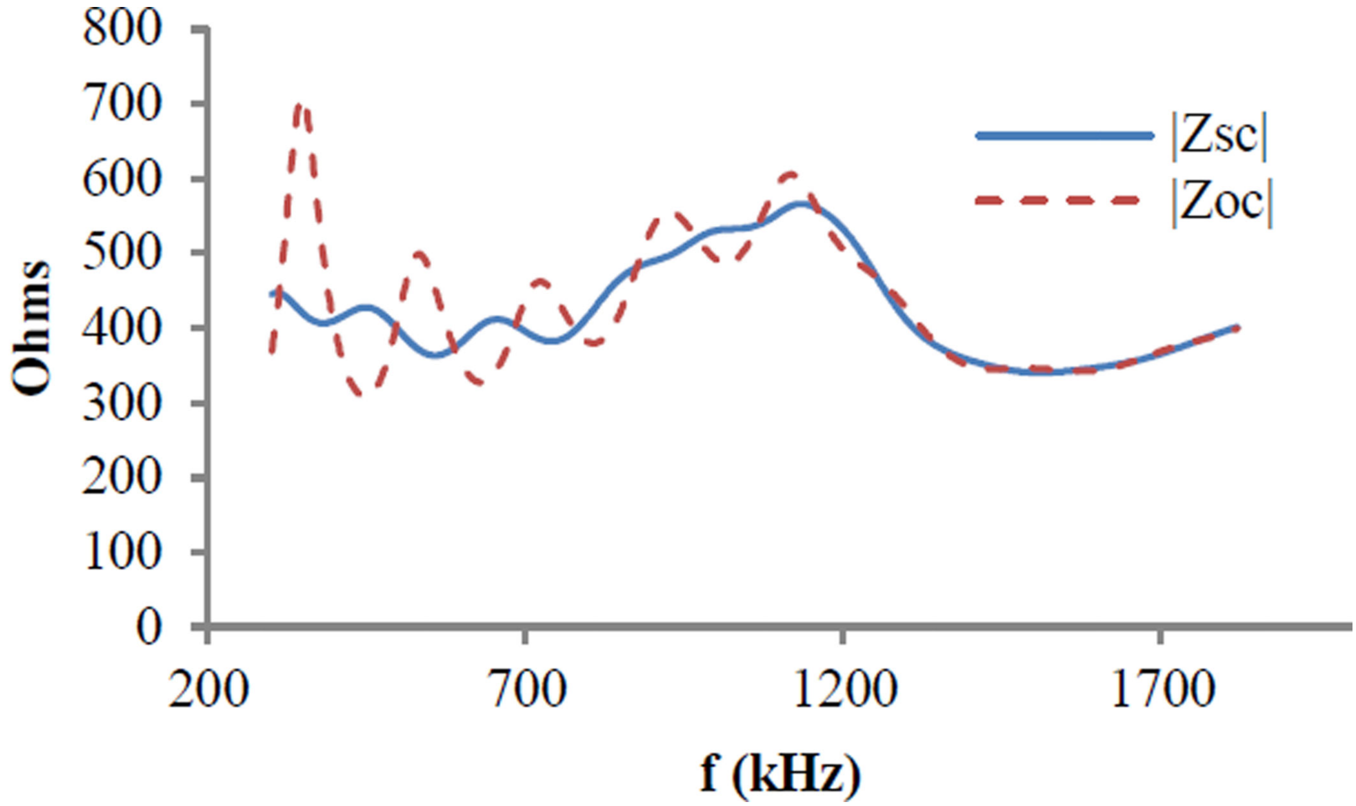

Fig. 5.

Open (dotted curve) and shorted (solid curve) line impedance measurements of the single-conductor wire TL on the floor

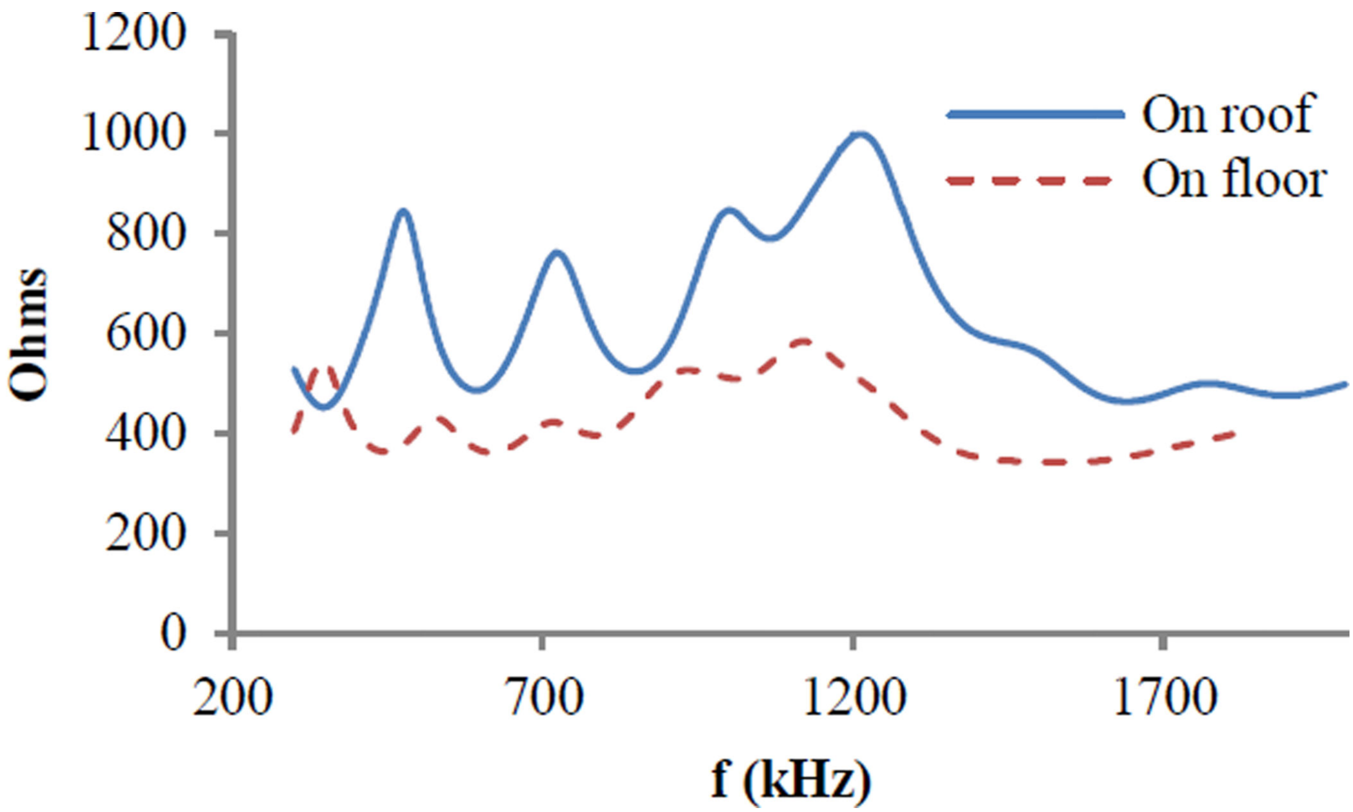

Fig. 6.
Characteristic impedances of the single-conductor wire TL on the roof (upper curve) and floor (lower curve)

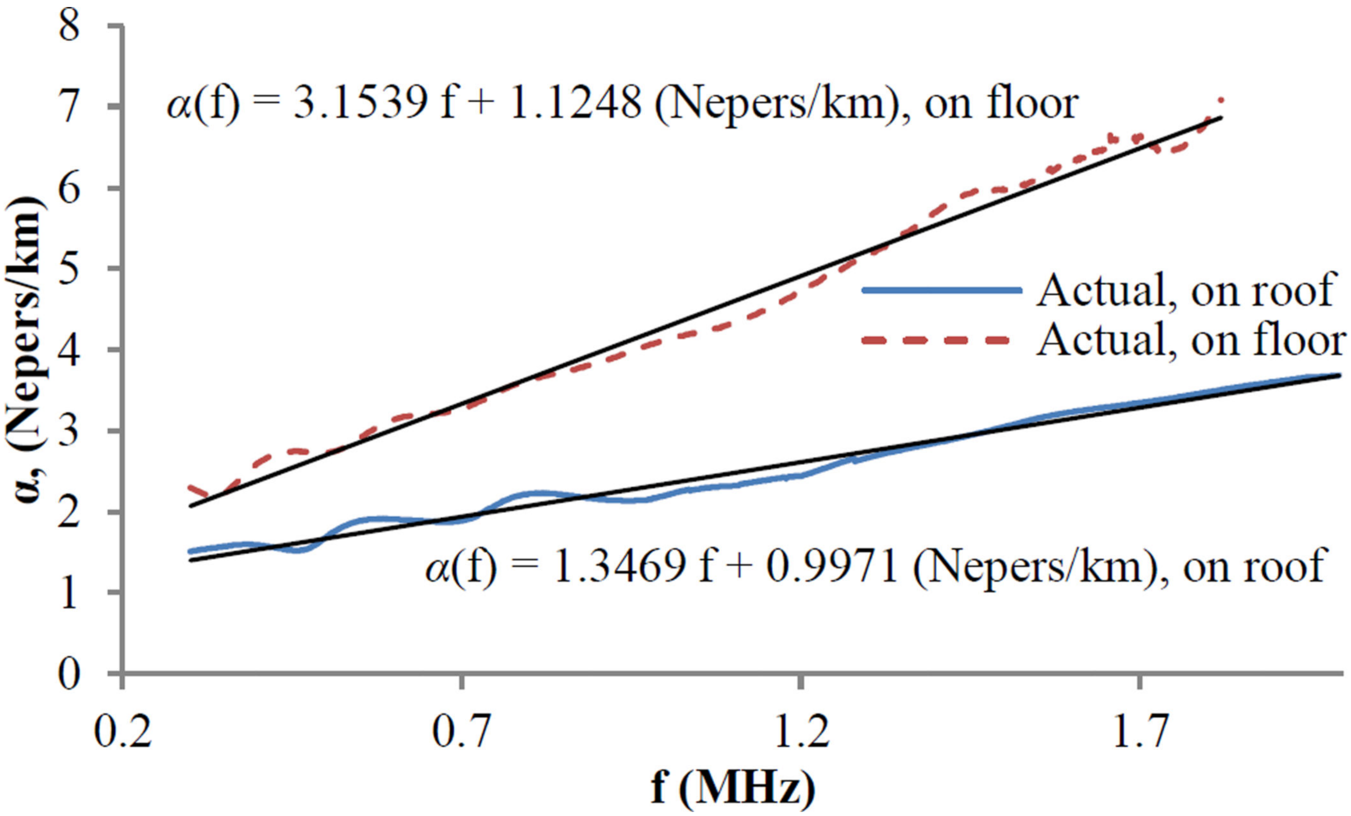

Fig. 7.

Attenuation constants of the single-conductor wire TLs on the roof (lower curve) and floor (upper curve)

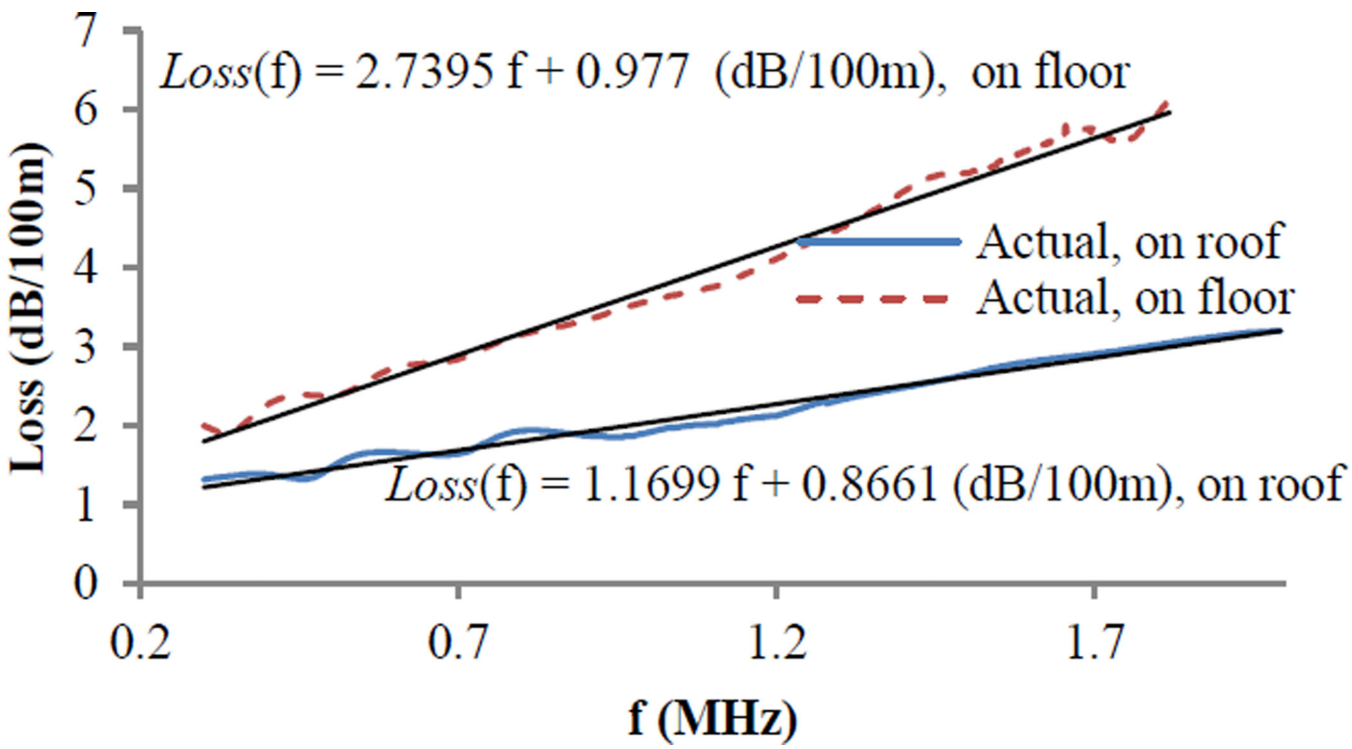

Fig. 8.

Power loss rates of the single-conductor wire TLs on the roof (lower curve) and floor (upper curve)

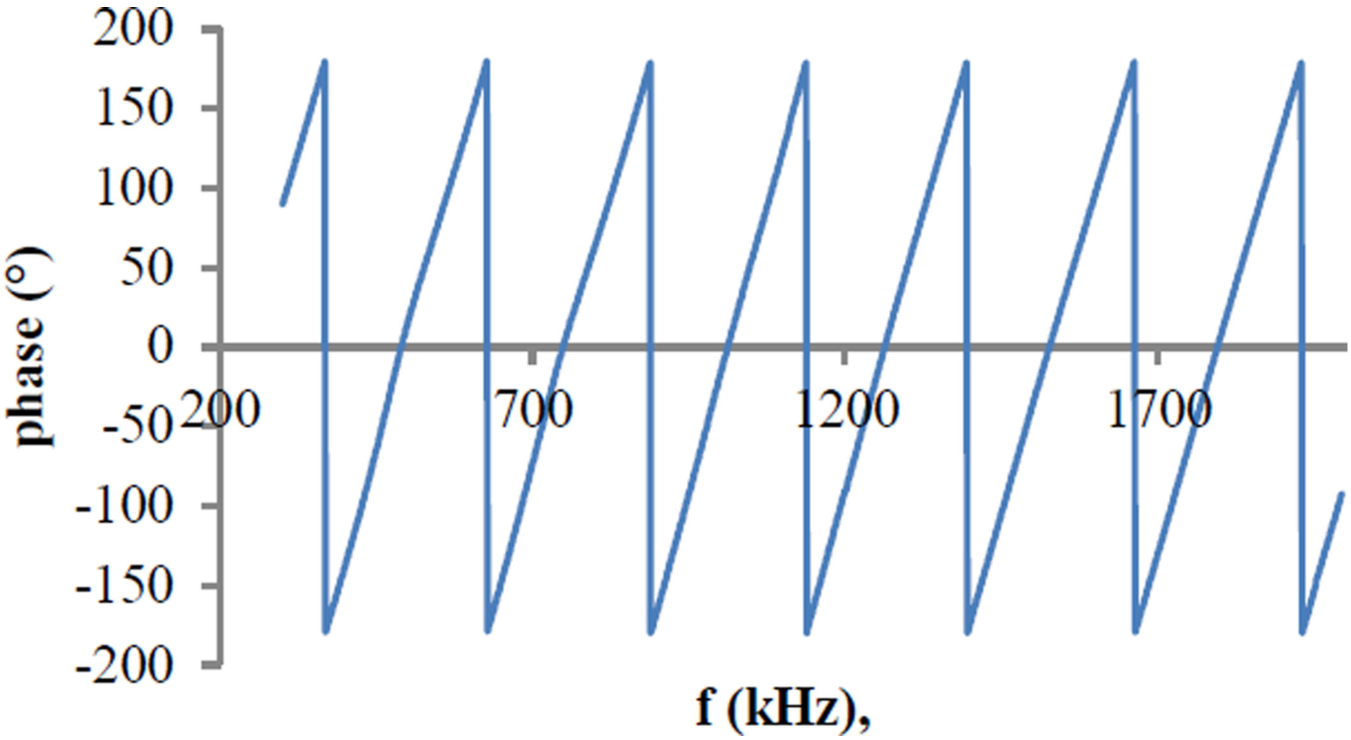

Fig. 9.
Input phase distribution, 2β(*f*)*l*, of the single-conductor wire TL on the roof

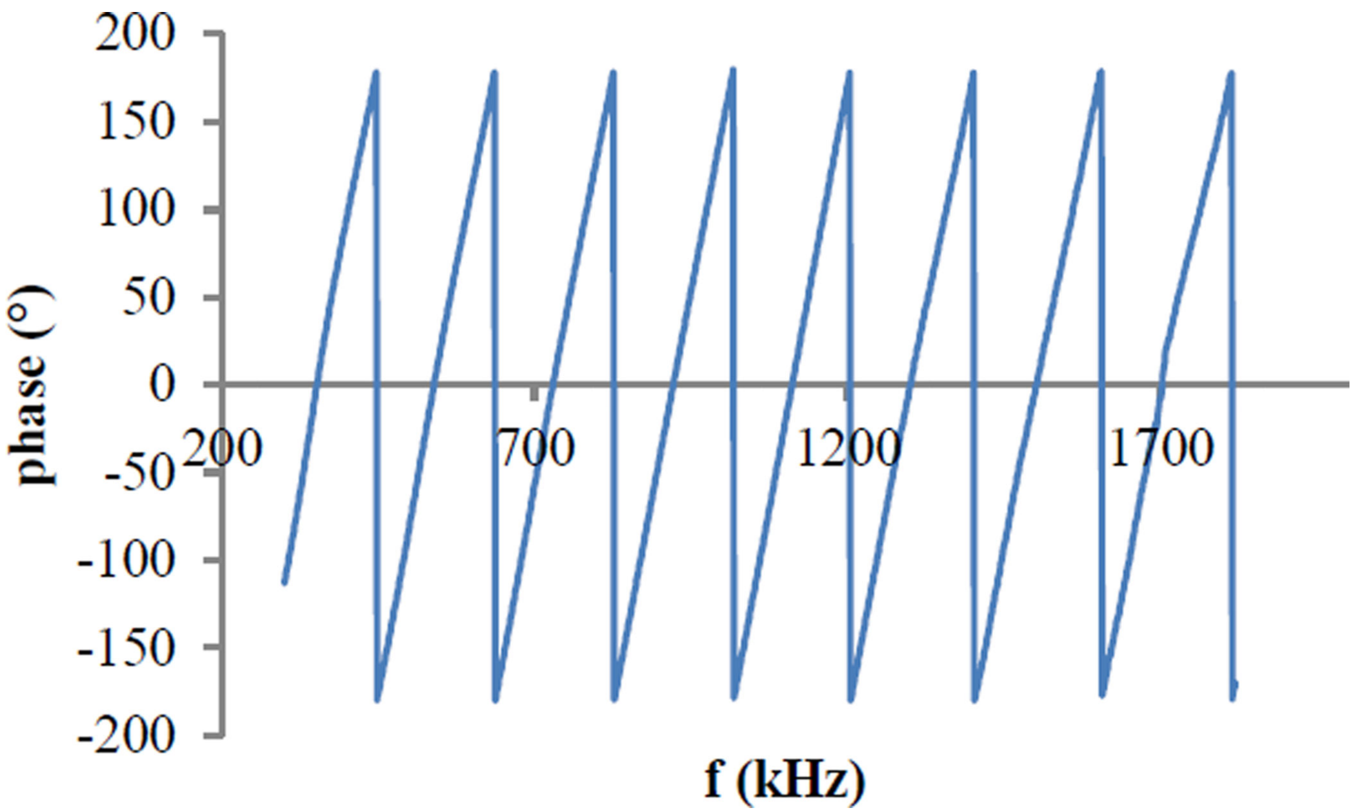

Fig. 10.
Input phase distribution, 2β(*f*)*l*, of the single-conductor wire TL on the floor

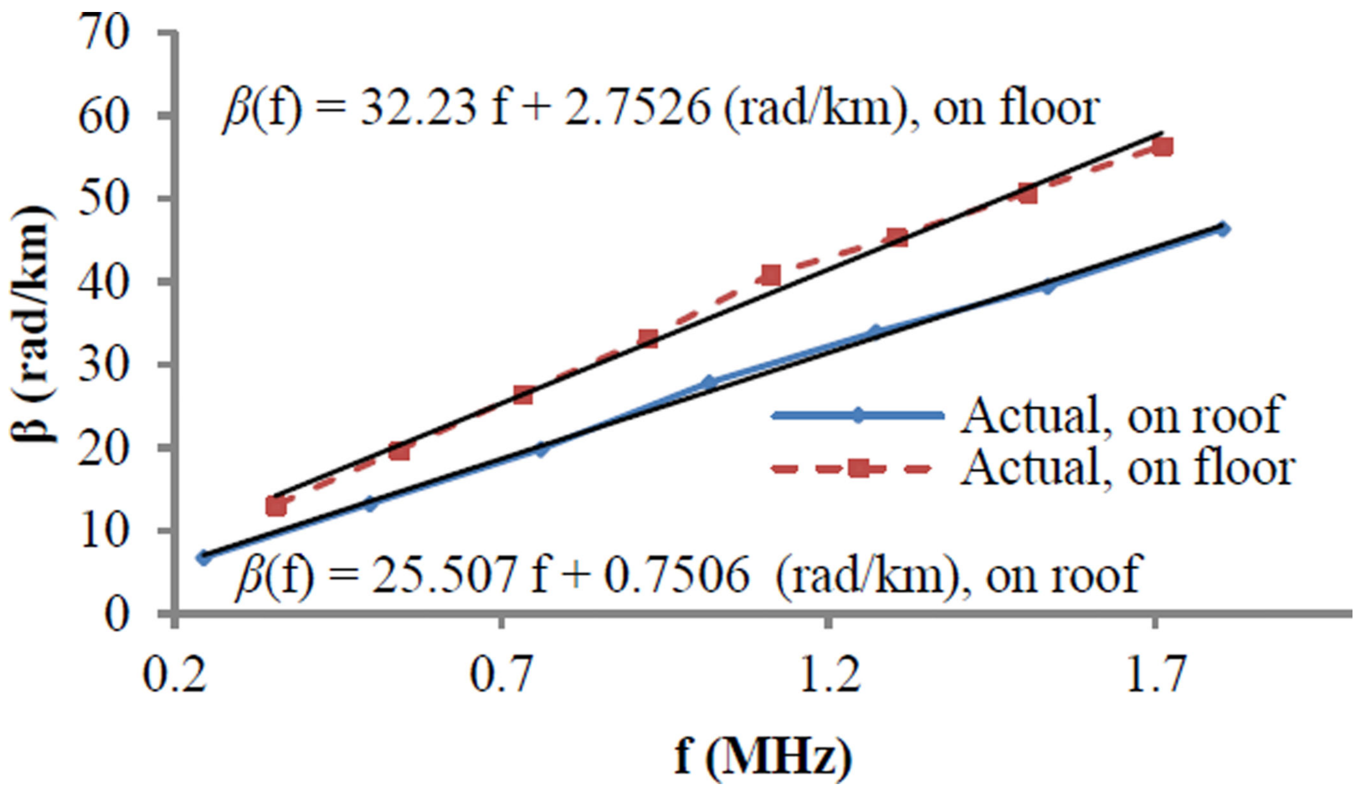

Fig. 11.

Phase constants of the single-conductor wire TLs on the roof (lower curve) and floor (upper curve)

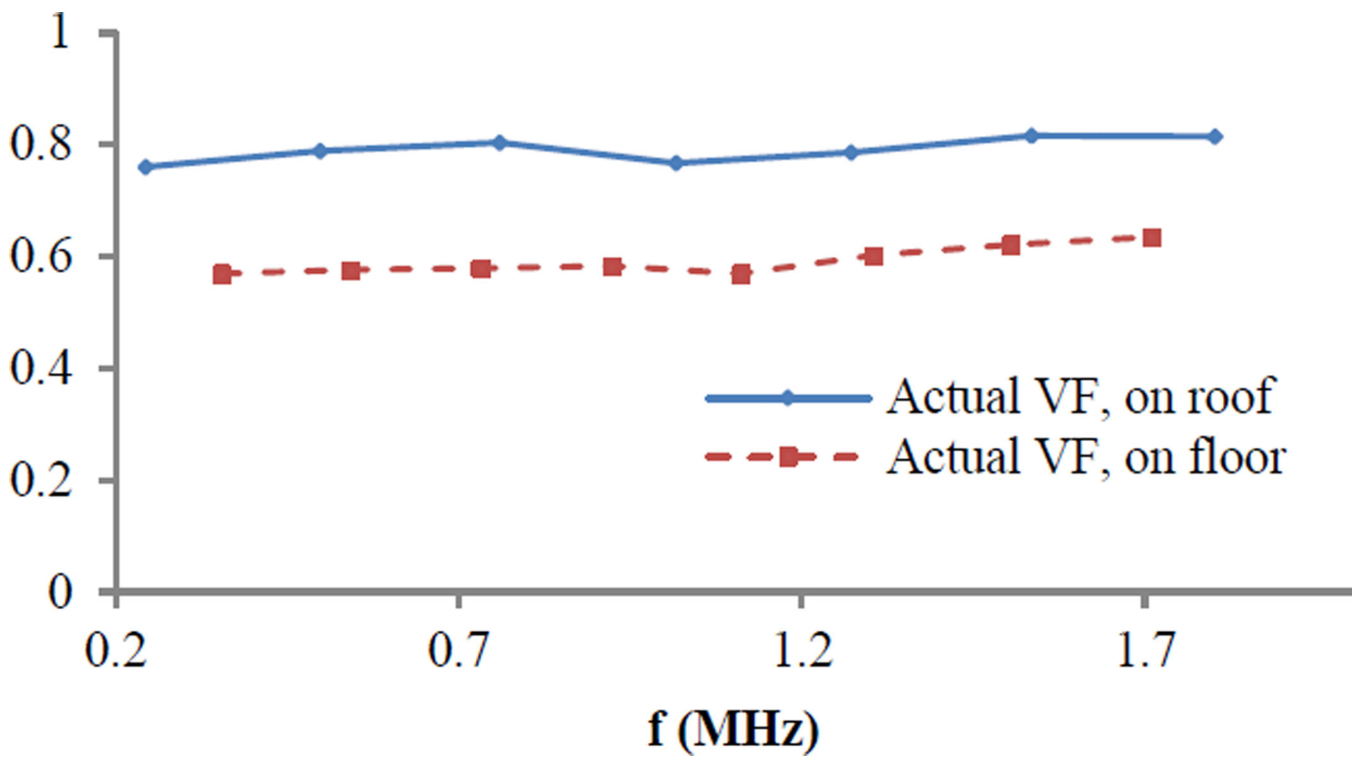

Fig. 12.
Velocity factors of the single-conductor wire TLs on the roof (upper curve) and floor (lower curve)

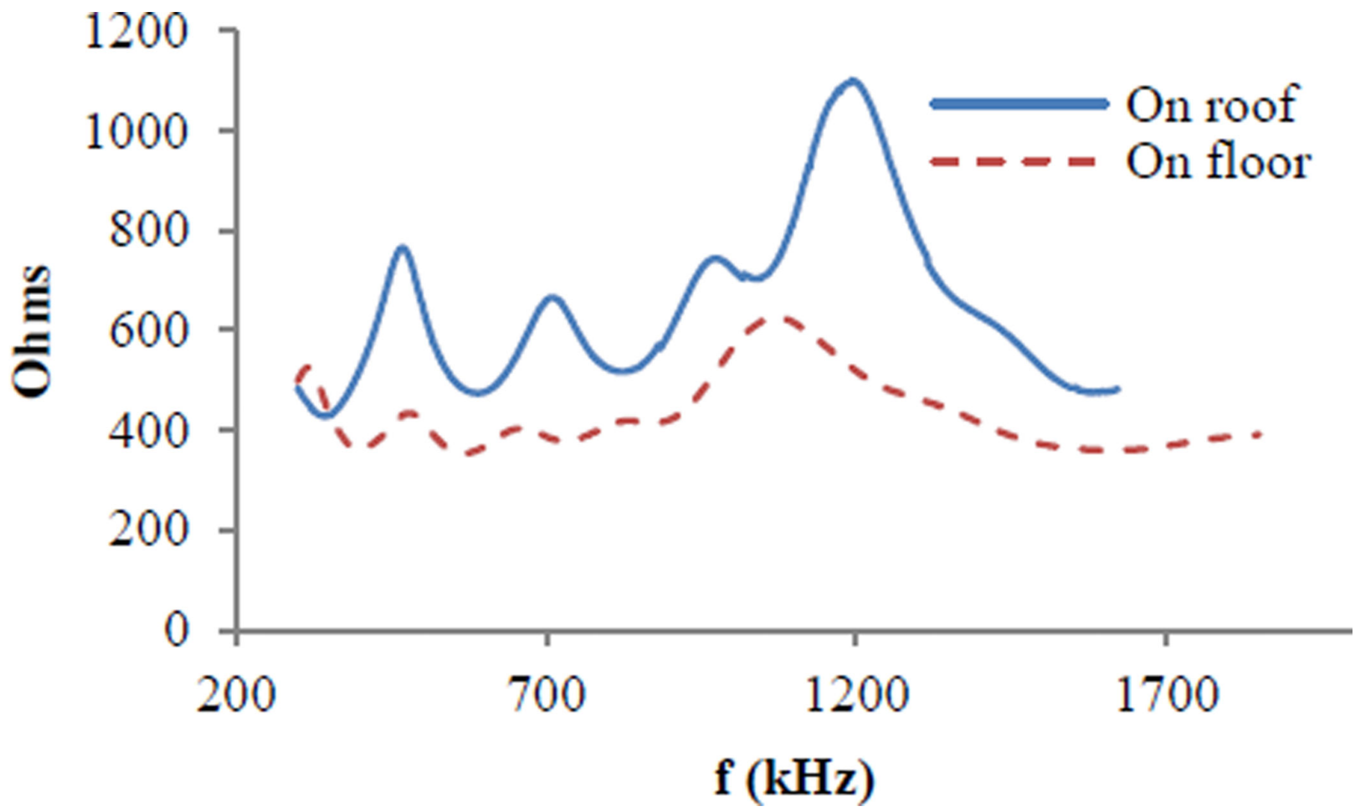

Fig. 13.

Characteristic impedances of the twisted cable configured in a single-conductor TL on the roof (upper curve) and floor (lower curve)

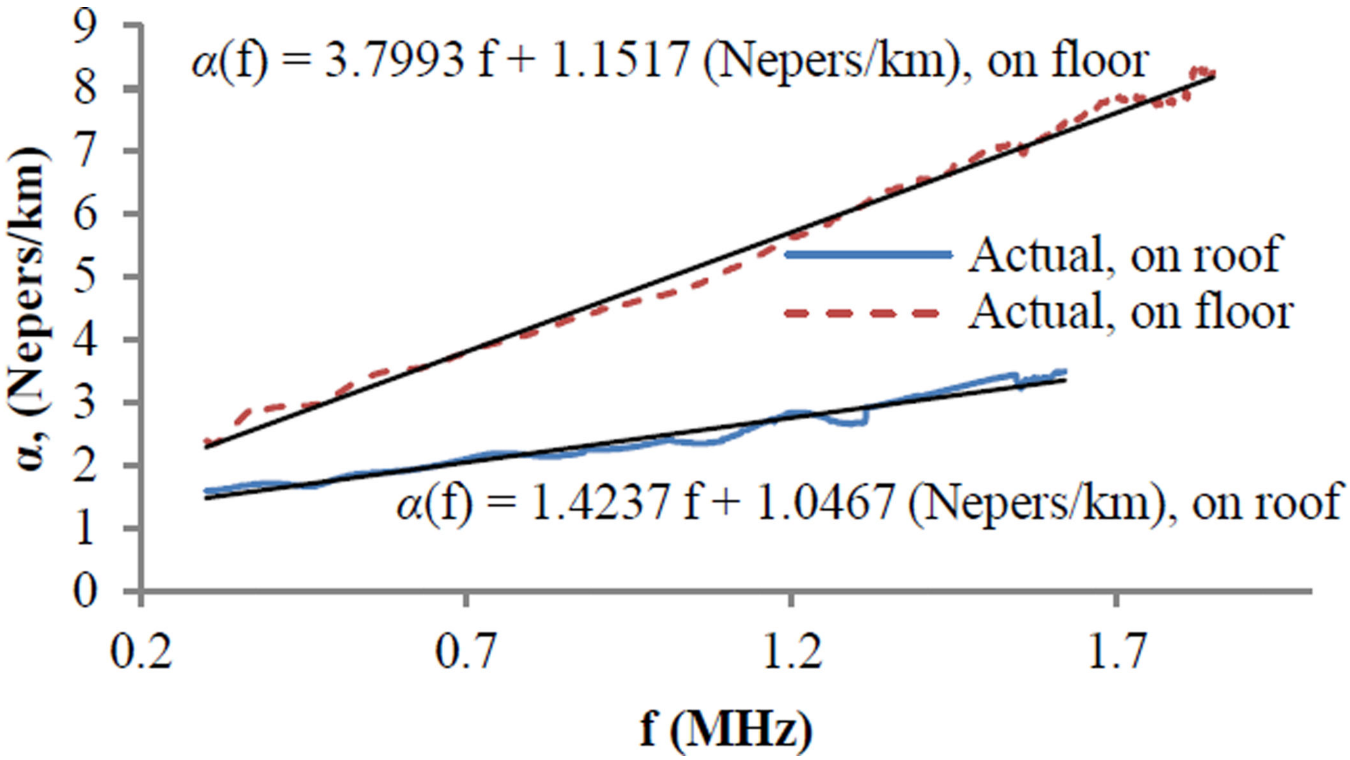

Fig. 14.

Attenuation constants of the twisted cable TLs on the roof (lower curve) and floor (upper curve)

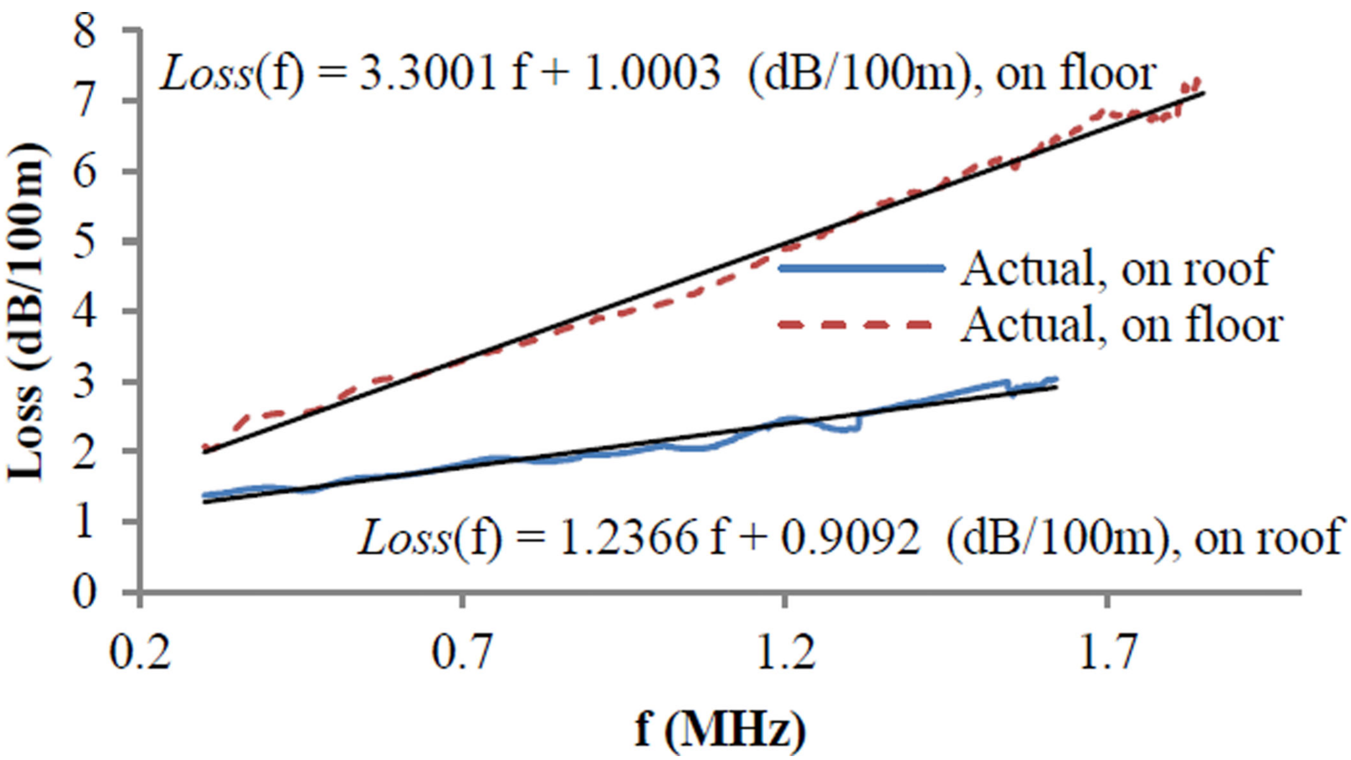

Fig. 15.
Power loss rates of the twisted cable TLs on the roof (lower curve) and floor (upper curve)

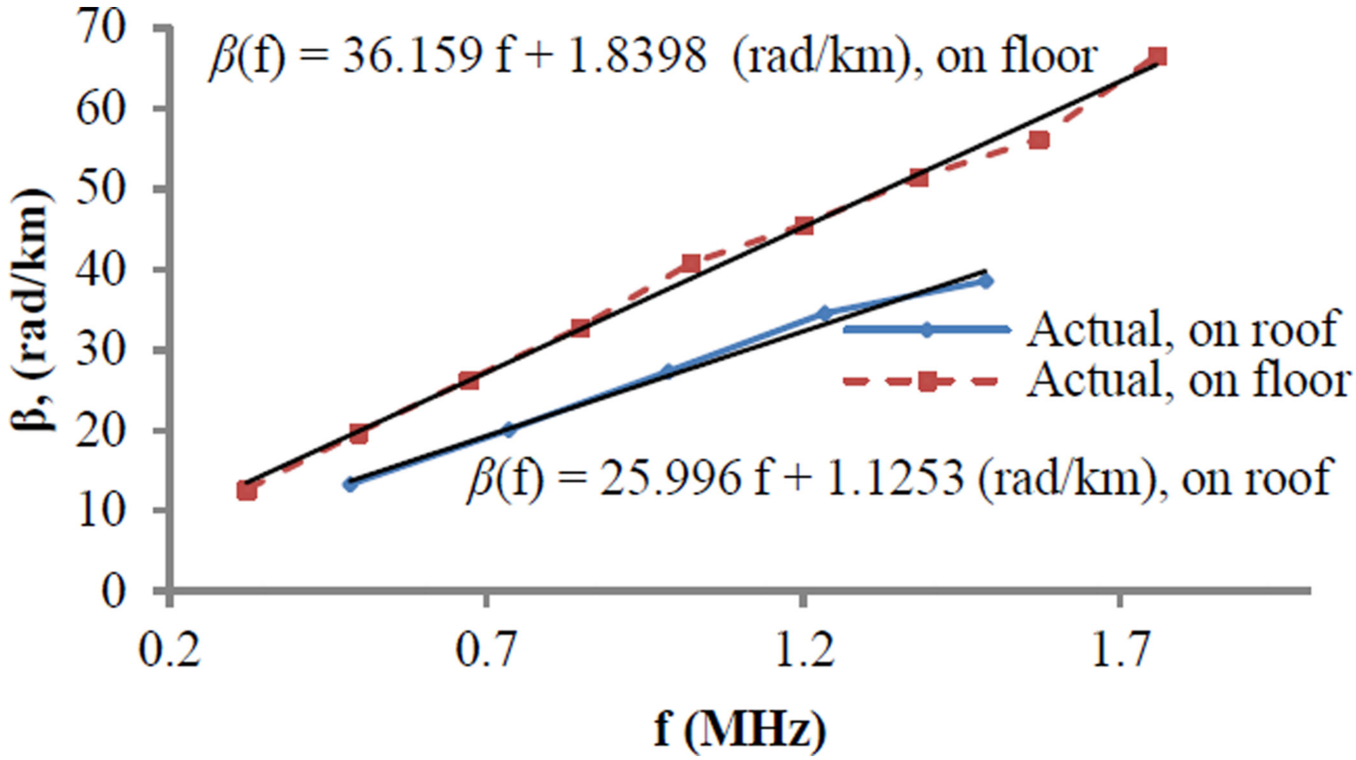

Fig. 16.
Phase constants of the twisted cable TLs on the roof (lower curve) and floor (upper curve)

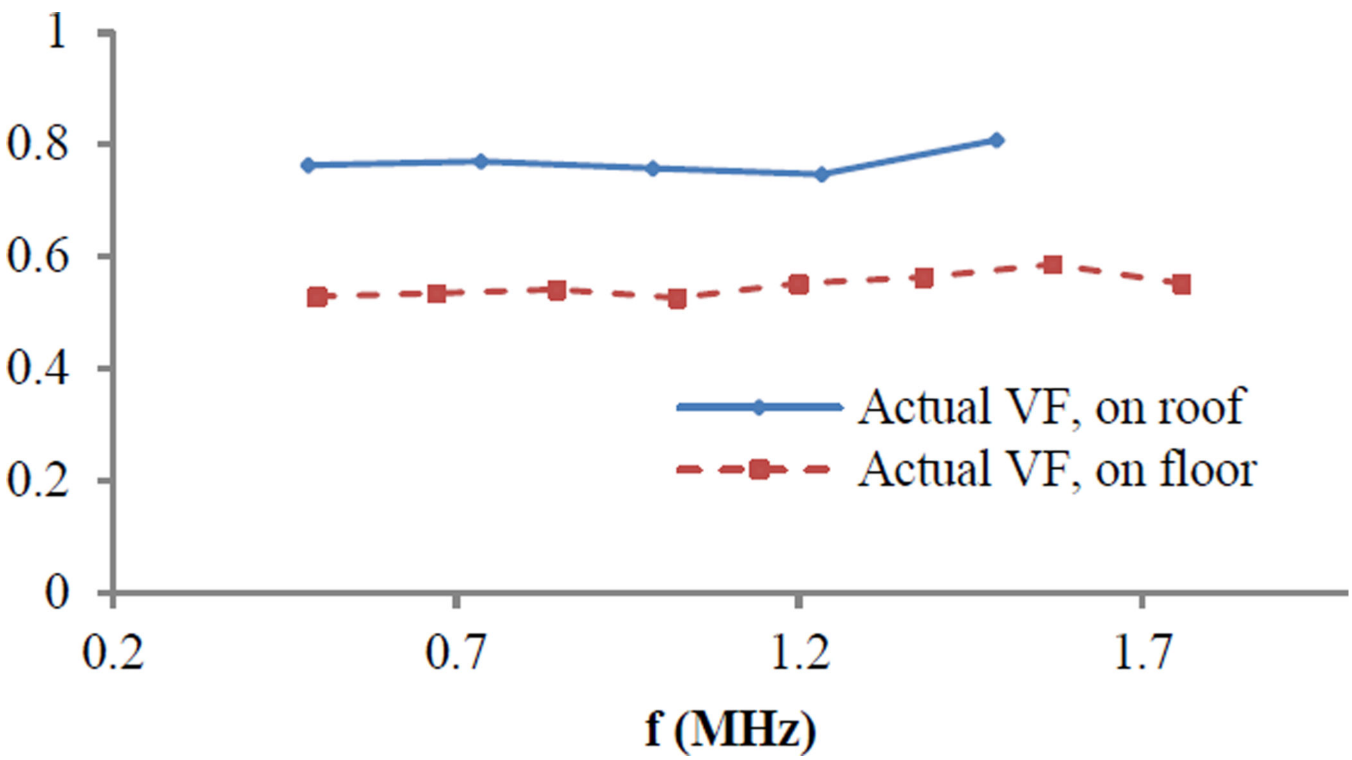

Fig. 17.
Velocity factors of the twisted cable TLs on the roof (upper curve) and floor (lower curve)

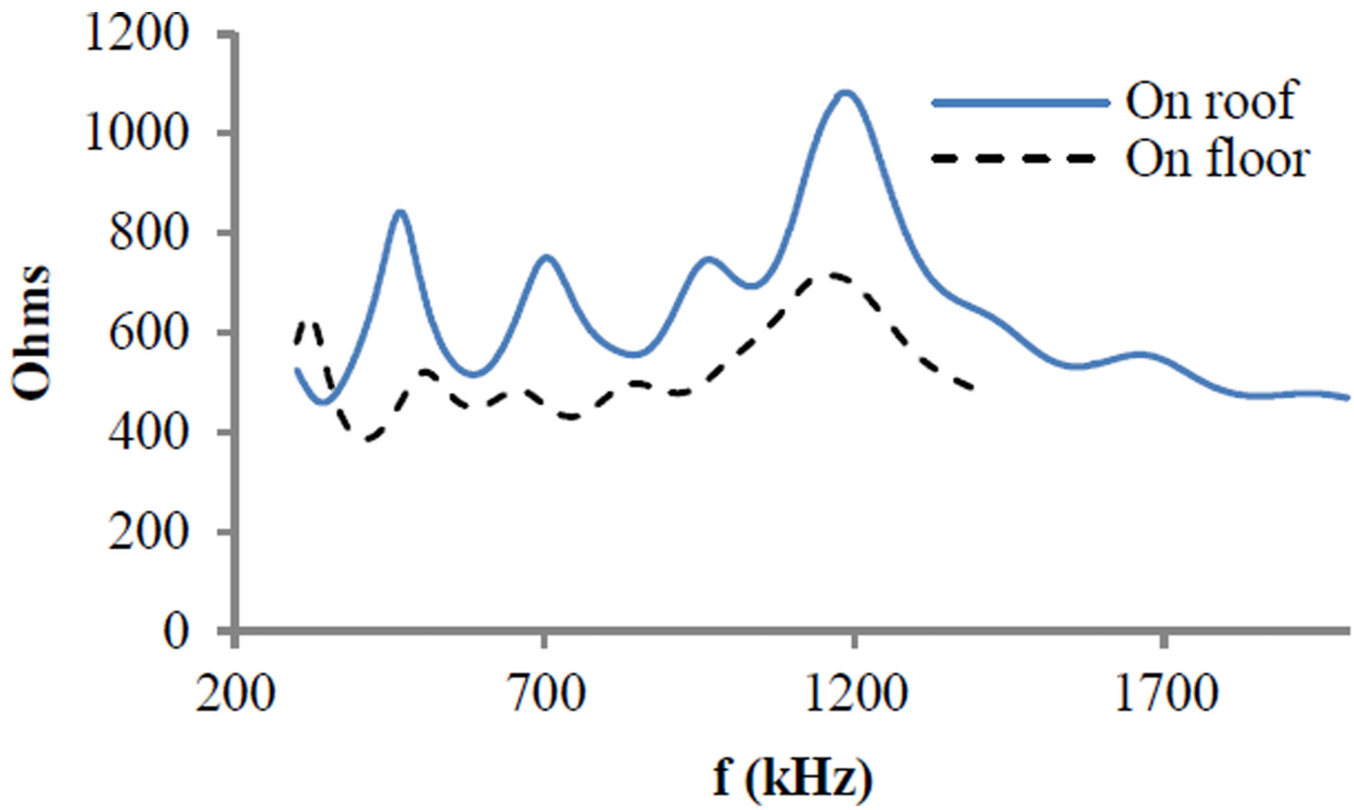

Fig. 18.
Characteristic impedances of the TV twin lead configured in a single-conductor TL on the roof (upper curve) and floor (lower curve)

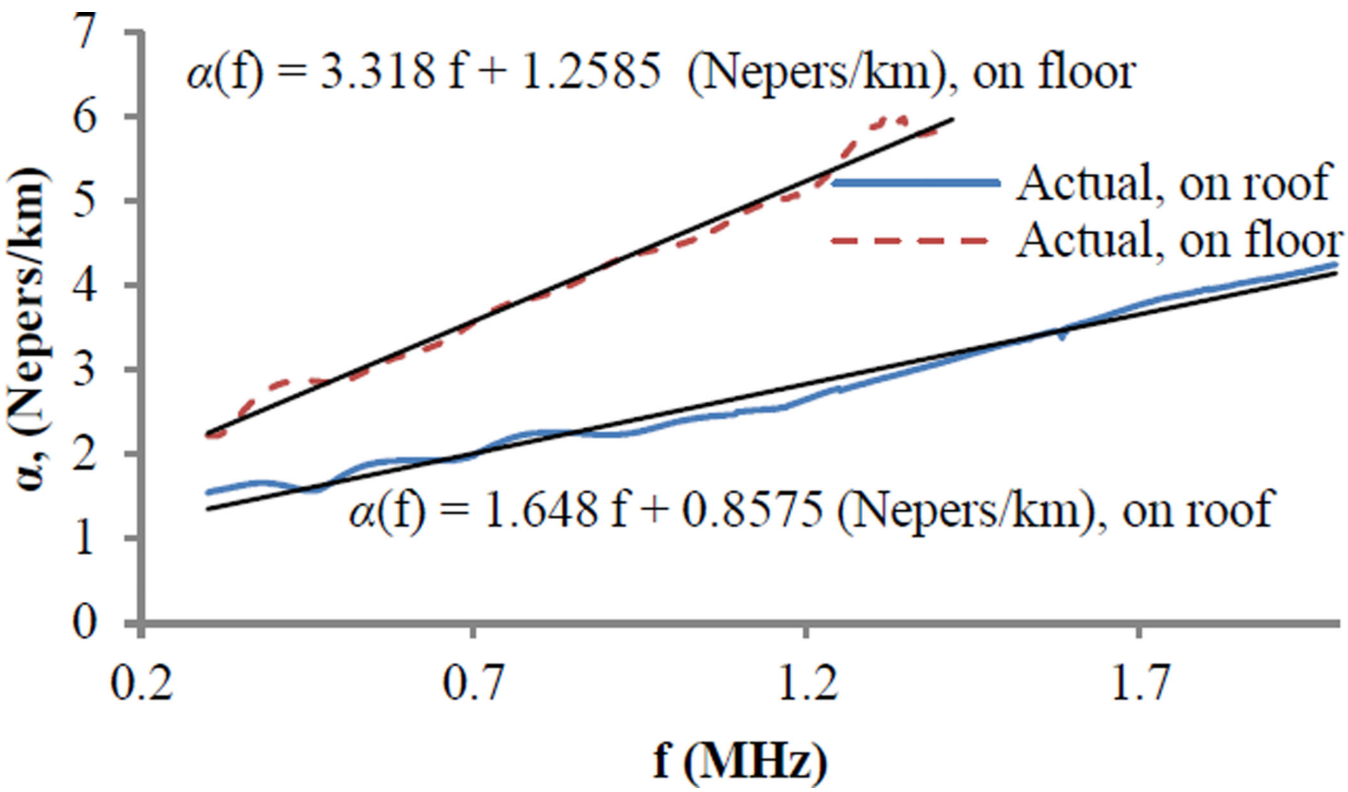

Fig. 19.

Attenuation constants of the TV twin lead TLs on the roof (lower curve) and floor (upper curve)

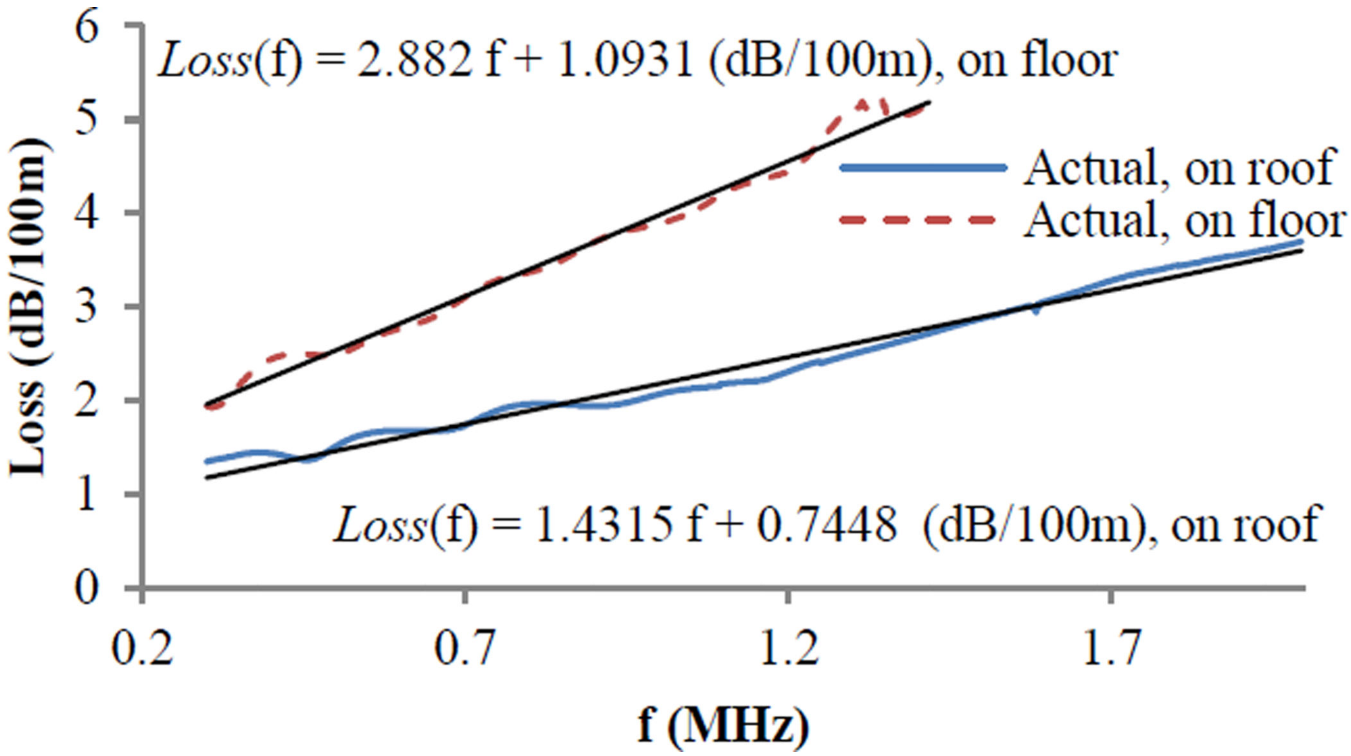

Fig. 20.
Power loss rates of the TV twin lead TLs on the roof (lower curve) and floor (upper curve)

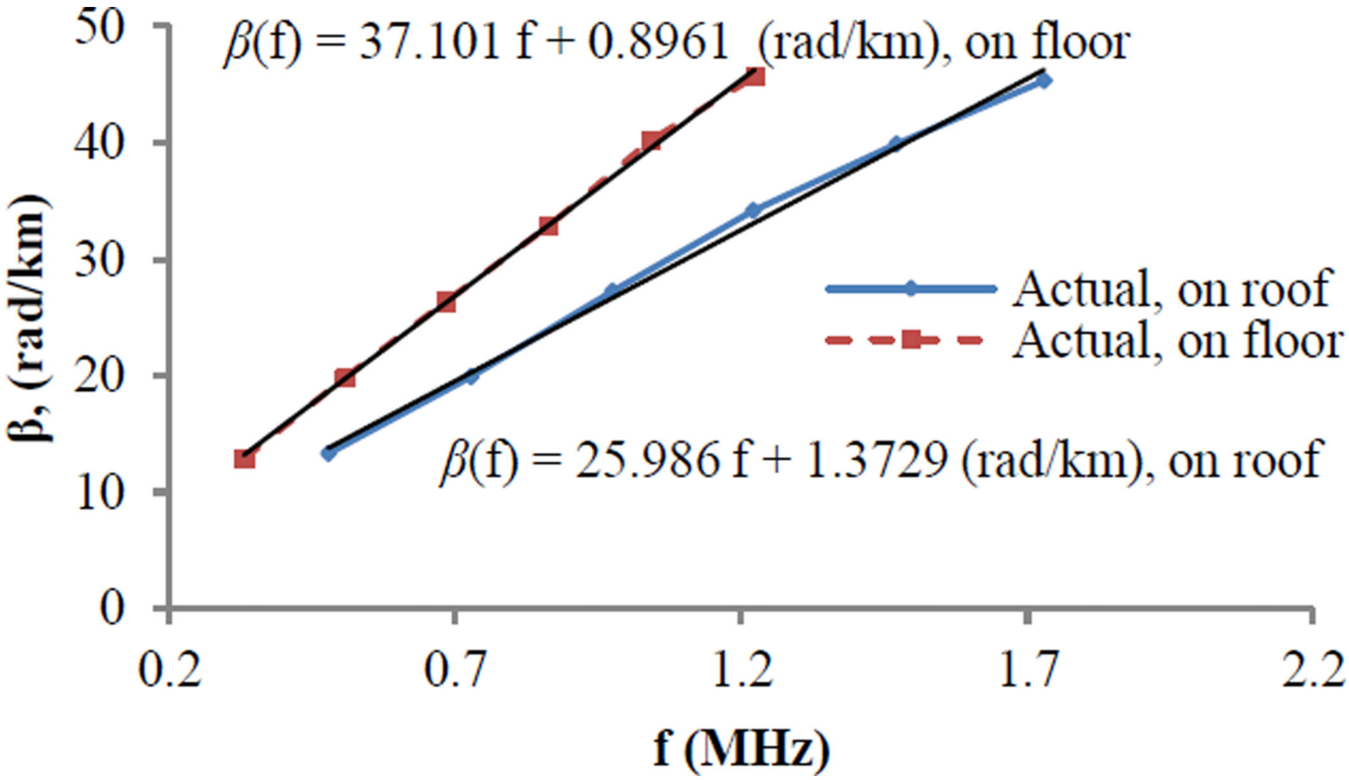

Fig. 21.
Phase constants of the TV twin lead TLs on the roof (lower curve) and floor (upper curve)

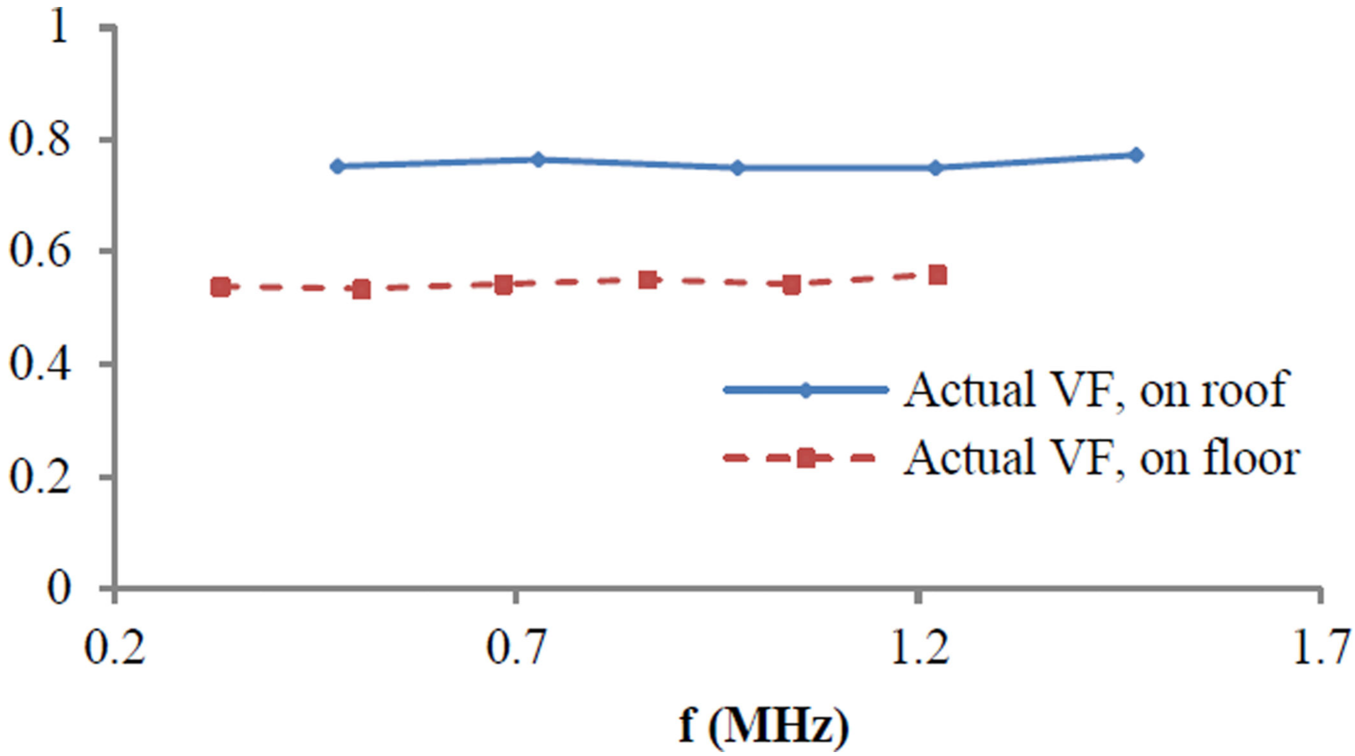

Fig. 22.
Velocity factors of the TV twin lead TLs on the roof (upper curve) and floor (lower curve)

TABLE I

FREQUENCY PAIRS RESULTING IN 2π PHASE ANGLES ON $2\beta(f_2)l - 2\beta(f_1)l$

Wire on roof		Wire on floor	
f_1 (Hz)	**f_2 (Hz)**	**f_1 (Hz)**	**f_2 (Hz)**
118,821	368,359	261,000	447,868
368,359	627,100	447,868	636,920
627,100	890,995	636,920	826,879
890,995	1,142,856	826,879	1,018,127
1,142,856	1,400,726	1,018,127	1,204,997
1,400,726	1,668,563	1,204,997	1,402,563
1,668,563	1,935,910	1,402,563	1,606,260
		1,606,260	1,814,751

TABLE II

PROPAGATION PARAMETERS OF THREE TYPES OF TLS ON THE ROOF AT *f* = 0.5 MHZ

	Single conductor	Twisted cable	TV twin lead
Characteristic impedance, (Ω)	749	652	704
Attenuation constant, (Nepers/km)	1.67	1.76	1.68
Power loss rate, (dB/100m)	1.45	1.53	1.46
Phase constant, (rad/km)	13.50	14.12	14.37
Velocity factor	0.79	0.77	0.76

TABLE III

PROPAGATION PARAMETERS OF THREE TYPES OF TLS ON THE FLOOR AT $f = 0.5$ MHZ

	Single conductor	**Twisted cable**	**TV twin lead**
Characteristic impedance, (Ω)	407	418	518
Attenuation constant, (Nepers/km)	2.70	3.05	2.92
Power loss rate, (dB/100m)	2.35	2.65	2.53
Phase constant, (rad/km)	18.67	19.92	19.45
Velocity factor	0.59	0.55	0.54