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Calculation of Electromagnetic Field Emitted from UTP Cable by Moment Method from 0.3 GHz to 2 GHz

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SUMMARY   The electromagnetic field emitted from UTP cable has been calculated by the 4-port network method from 30 MHz to 1 GHz. However it has not been clarified as to whether this method was effective in the frequency range of more than 1 GHz or not. In this paper, the electromagnetic field emitted from UTP cable was calculated by the moment method and it was compared with the calculated results by the 4-port network method. The wire grid model was developed to represent the propagation constants of UTP cable. The comparison of calculated and measured results confirms the validity of the model. A hybrid coupler was used to generate differential mode signal for the measurement. The comparison indicated that the calculated results by the moment method closely agreed with the measured results in the frequency range of 0.3 to 2 GHz and the difference was smaller than the results by the 4-port network method.
key words: *UTP, radiation, wire grid*

1. Introduction

UTP (Unshielded Twisted Pair) cable is widely used as telecommunication cable because it can provide an economical telecommunication system and is easy to handle compared with optical fiber [1]. The signal speed propagating on UTP cable is increasing by the advancement of the telecommunication technology, and the system of 10 Gbps is being developed [2].

The possibility of the electromagnetic field leaking from UTP cable increases when a high-speed signal is transmitted on the cable. Therefore, the electromagnetic field emitted from UTP cable has been analyzed. Several analysis methods, such as the finite integration technique [3], the moment method [4], and the 4-port network method [5], have been studied to calculate the radiated field. The finite integration technique [3] has the advantage of providing full wave analysis. However, a lot of memories and computing time are needed. The moment method [4] also provides full wave analysis, but it is difficult to treat the dielectric material of the cable. On the other hand, the 4-port network method [5] has the advantage that the characteristic impedance and the propagation constant of the cable can be considered. However, this model can not consider the emission from the differential mode current. Therefore, the upper frequency limit exists in this method.

Recent report suggests that the 4-port network method can be applied up to 1 GHz [5]. However, it is not understood whether this method can be used at more than 1 GHz because this method assumes that the field is radiated only from the common mode current and that only TEM mode propagates on the cable. The possibility of the radiation from the differential mode current and of other mode generation increases at more than 1 GHz. Therefore, we should study the method of calculating the field at more than 1 GHz.

This paper presents the calculation method of electromagnetic field emitted from UTP cable by the moment method. The wire grid model is used to represent the UTP cable and the telecommunication equipment. The characteristic impedance and the propagation constant of the cable are modeled by modifying the wire radius and by inserting the capacitance between wires. These values by the proposed wire grid model are compared with theoretical and measured values.

The common-mode current distribution and the radiated field are calculated by the new wire grid model. The 4-port network model is also introduced according to the reference [5], and the common-mode current distribution and the radiated field strength are calculated. The radiated field is measured in an anechoic chamber from 0.3 GHz to 2 GHz. The hybrid coupler is used as the telecommunication equipment, and the measured S-parameters are used to create the wire grid model. These results are compared with each other to confirm the validity of the developed wire grid model.

2. Wire Grid Model of UTP Cable

Figure 1 shows the analytical model of the electromagnetic
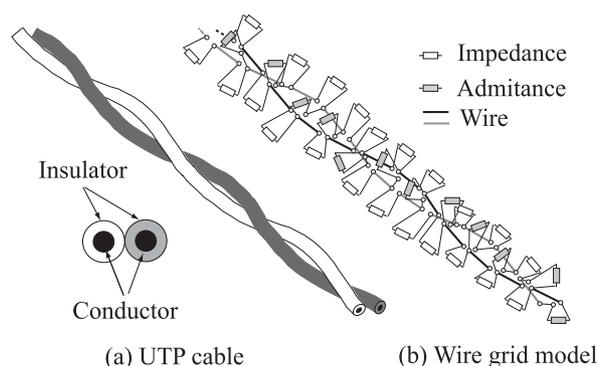
Fig. 1   UTP cable and proposed wire grid model.

field emitted from UTP cable. UTP cable has multi pairs, but it is difficult to treat the multi-pair conditions. Therefore, we consider one twisted pair with no branch as shown in Fig. 1(a). Although the length of actual UTP cable is several tens meters, we consider the length of several meters because of the computer performance and the measurement facility limits. Both ends of cable are terminated by the telecommunication equipment.

Proposed wire grid model of UTP cable is shown in Fig. 1(b). The permittivity of the insulator and the finite conductivity of the conductor are included by inserting an impedance and admittance into the wire model with perfect conductor and in free space, as shown in Fig. 1(b).

The method of obtaining an insertion impedance and admittance value has not been clarified. Then, we study the method of determining these parameters in the next section.

2.1 Method of Creating Wire Grid Model

It is difficult to present the effect of dielectric material (insulator) of UTP cable by the wire grid model. However, the presented paper [6] suggests that the effect of dielectric material can be modeled by inserting an impedance and admittance into the wire grid model. Then, we study the method of representing UTP cable by the wire grid model.

In many cases, UTP cable is placed at sufficiently high position from the ground plane compared with the distance between conductors. Therefore, we assume that the dielectric material does not influence to the transmission characteristics between the ground and the conductors. The wire grid model is designed by considering only the characteristic impedance and the propagation constant of the transmission line between conductors.

When we consider the transmission characteristics for the cable of several meters, we need not consider the transmission loss. In this case, the transmission characteristic of the line, where only TEM mode propagates, is represented by the inductance and the capacitance per unit length. Therefore, we study the method of presenting the inductance and the capacitance by the wire grid model.

Transmission loss might influence to the radiated electromagnetic field when the cable length is sufficiently long. However, it is difficult to calculate the radiated field from a long cable because of the limit of the number of wires. The calculation example by the 4-port network method suggested that the radiated electric field did not change at 200 MHz when the cable length is more than 5 m [7]. Therefore, we consider that the radiation characteristics can be obtained by the cable of several meters. The calculation of the radiated field for a long cable is a future problem.

2.2 Determination of Wire Radius and Insertion Capacitance

Figure 2 shows the procedure of creating wire grid model. Figure 2(a) presents the cross section of UTP cable. The radius of the conductor is 0.25 mm, the dielectric constant

(a) Configuration of UTP cable

(b) Model wire radius modified   (c) Wire grid model of UTP cable
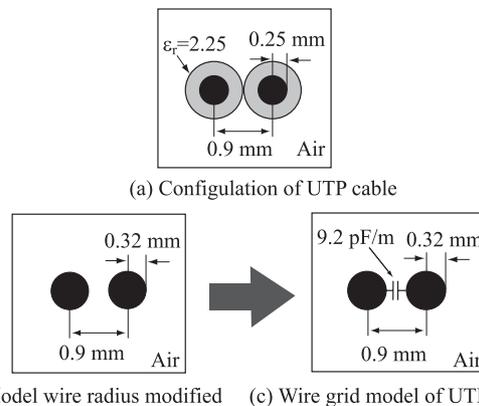
Fig. 2 Method of determining wire radius and inserting capacitance.

of the insulator is 2.25, and the distance between the two conductors is 0.9 mm. These values are obtained from specifications of category 5 LAN cable. The wire grid model of the cable is determined by the following process.

1. First, the radius of the wire is selected as the inductance of the wire grid model is equal to the theoretical value as shown in Fig. 2(b). The theoretical value can be calculated on the condition that the insulator does not affect the value because the permeability of the insulator is the same as free space.
2. The effect of the dielectric material on the capacitance per unit length can be included by inserting the capacitance, C, between the wires as shown in Fig. 2(b). The value, C, is calculated by Eq. (1).

$$C = C_{12} - C_{OS} \tag{1}$$

In Eq. (1), C_{12} is the capacitance per unit length of UTP cable shown in Fig. 2(a), and this value is calculated by FEM [8]. C_{OS} is the capacitance per unit length of the wire model in Fig. 2(b), and this value is calculated by electro-static theory [9]. The capacitance of the difference between the capacitance of UTP cable and the capacitance of the wire model is inserted between wires as shown in Fig. 2(c) according to the reference [6].

The open-short method [10] is used to determine the inductance and capacitance per unit length of the wire grid model. The concept of the open short method is shown in Fig. 3. First, we calculate the input impedance when the far end is shorted as shown in Fig. 3(a). Here, the far end means the opposite side of the position where the signal source is connected. The input impedance, Z_S, is given by;

$$Z_S = \frac{V_S}{I_S} \tag{2}$$

Second, we calculate the input admittance when the far end is opened as shown in Fig. 3(b), and this is given by;

$$Y_O = \frac{I_O}{V_O} \tag{3}$$
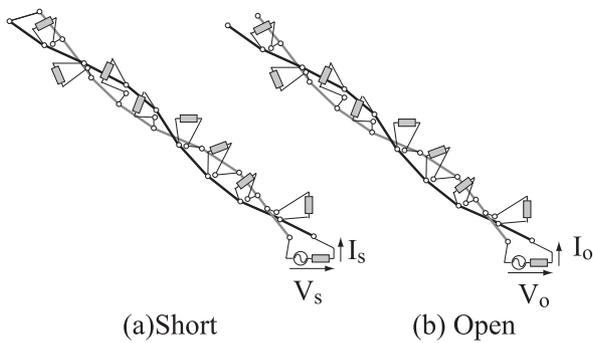
Fig. 3   Concept of the open short method.
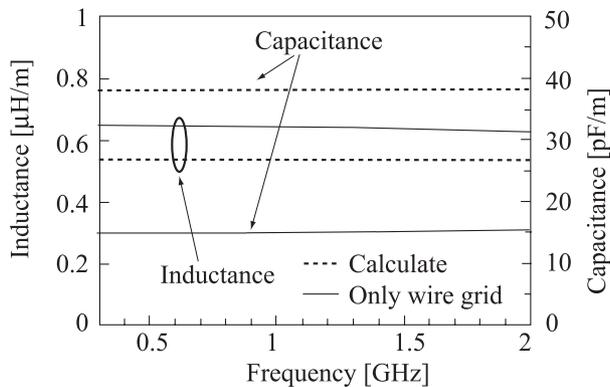
Fig. 4   Calculated results of inductance and capacitance per unit length.

Fig. 5   Calculated results of characteristic impedance and phase constant.
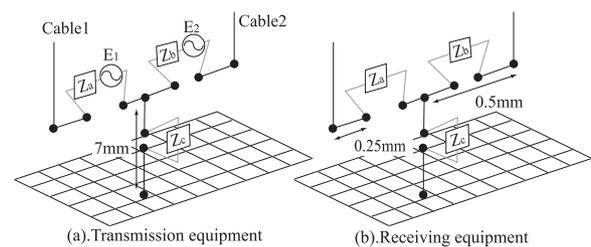
Fig. 6   Wire grid model of telecommunication equipment.

From Z_S, Y_O, and line length, the inductance and capacitance per unit length are obtained. NEC2 (Numerical Electromagnetic Code 2) [11] was used for the calculation.

2.3   Characteristic Impedance and Phase Constant of Wire Grid Model

The calculation example is shown in Figs. 4 and 5. On the calculation, the length of 17 mm was used as the cable length. This value was selected from the length of one twist of UTP cable, and this length was sufficient short compared with the wavelength at 2 GHz. As shown in Fig. 2(c), the radius of 0.32 mm and the insertion capacitance of 9.2 pF/m have been determined from the investigation, and these values were used for calculation.

Figure 4 shows the calculated results of the inductance and capacitance per unit length. In this figure, the dotted line indicates the value obtained by using the model shown in Fig. 2(c), and the solid line indicates the value on the condition that the radius of the wire is 0.25 mm and that the capacitance is not inserted between wires.

The result shows that the parameters per unit length are almost constant from 0.3 GHz to 2 GHz. This means that the parameters per unit length can be calculated by the open short method because the theoretical value assuming TEM mode is independent of frequency. The dotted line also indicates the capacitance and inductance per unit length of the UTP cable, and the solid line indicates the values on the

condition that the dielectric material of the cable is not considered. The capacitance of UTP cable is larger than the value without the dielectric material because it increases the capacitance between the wires. The inductance is slightly smaller than the value of the perfect conductor by the influence of the current distribution in the conductor. The result in Fig. 4 indicates that the model in Fig. 2 well presents the capacitance of the cable.

Figure 5 shows the characteristic impedance and phase constant of UTP cable shown in Fig. 2(a). The solid line is analytical value, the dotted line is calculated value by the proposed model, and the circle is measured value. The analytical value was calculated from the theoretical value of the inductance and capacitance per unit length by FEM. The measured values were obtained from the current distribution on the wire by using the method described in Sect. 3.2. These results show that the calculated value closely agrees with the theoretical value and the measured value. This means that the proposed modeling method can be used to create the wire grid model of UTP cable.

2.4   Model of Telecommunication Equipment

The UTP cable is terminated by telecommunication equipment. The wire grid model of the telecommunication equipment is shown in Fig. 6. The telecommunication equipment is represented by the T type network, which is constructed with impedance of Z_a, Z_b, and Z_c. The wire grid model is created by the six wires. The lengths of wires between conductors are 0.5 mm and the length of wire between conductors and ground is 7 mm. The impedances are inserted at the

junction point of each wire. For the transmitter, the voltage sources are also inserted in the model in series of Z_a and Z_b respectively.

3. Experiment

The current distribution and radiated electric field strength were measured to confirm the validity of the proposed wire grid model. This section describes the measurement method and the results.

3.1 Equivalent Circuit of Hybrid Coupler

In this paper, the transmitter is replaced by a differential mode signal source. A balun has been used to generate the differential mode signal. However, there is no balun operating more than 1 GHz. Therefore, we used a hybrid coupler to generate the signal.

External view of the hybrid coupler used in this experiment is shown in Fig. 7. The coupler has four ports. The A port is the input port, the C port is the output port where the phase difference from the input port is 0 degree, the D port is the output port where the phase difference from the input port is 180 degrees, and the B port is terminated by 50 Ω.

The S-parameters of the network composed of A port, B port, and C port were measured to determine the value of the impedances and the voltage sources shown in Fig. 6. The method of determining these values is presented in the reference [5]. Figure 8 shows the measurement result of the impedances, Z_a, Z_b, and Z_c. The measurement frequency range is from 0.3 GHz to 2 GHz. The upper frequency is limited by the frequency range of the coupler. As shown in this figure, $|Z_a|$ and $|Z_b|$ are almost 50 Ω, and $|Z_c|$ is almost 0 because the external conductor of the output ports is connected to the metallic case of the hybrid coupler directly. The range of the phase angle of Z_a and Z_b is within 20 degrees. Although the phase angle of Z_c changes from −180 degrees to 180 degrees, the influence to the calculation results is small because the $|Z_c|$ is almost zero.

These results indicate that the differential mode signal can be generated by the hybrid coupler. In this paper, these measurement values were used for the calculation.

3.2 Measurement of Current Distribution

The current distribution on the cable was measured to con-

firm the validity of the analytical model. The experimental set up is shown in Fig. 9. Figure 9(a) shows a view of experimental set-up and Fig. 9(b) shows the experimental layout. The UTP cable, whose length is 50 cm, was placed on the styrene foam, and the hybrid couplers were connected at both ends of cable. The D and C ports of these couplers in Fig. 7 were connected to each conductor of the cable. The A port of one of the couplers was connected to a signal generator, and the differential mode signal was supplied to the cable. The A port of the other coupler was terminated by
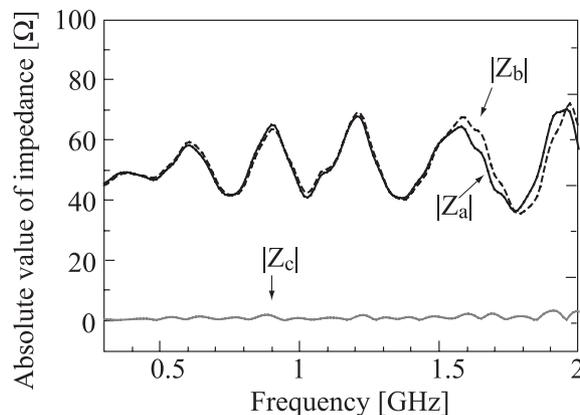
Fig. 8 Measured result of impedances used wire grid model.
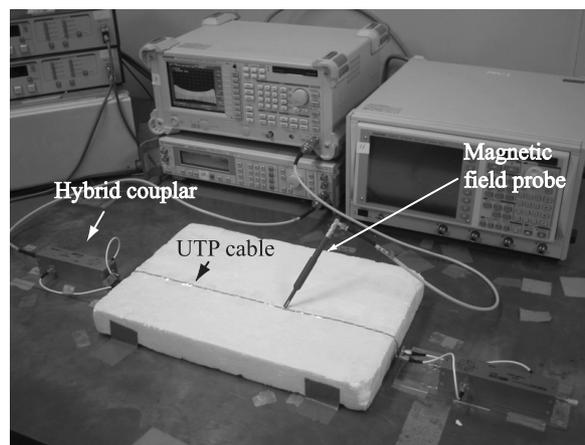
(a) External view
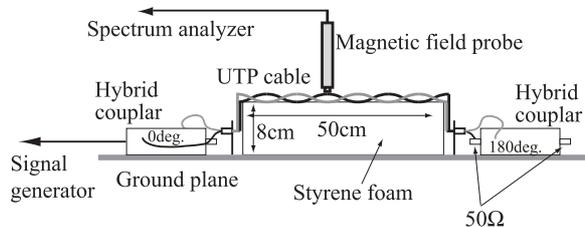
(b) Experimental set-up

Fig. 9 External view and experimental set-up for measuring current distribution.

Fig. 7 External view of hybrid coupler.
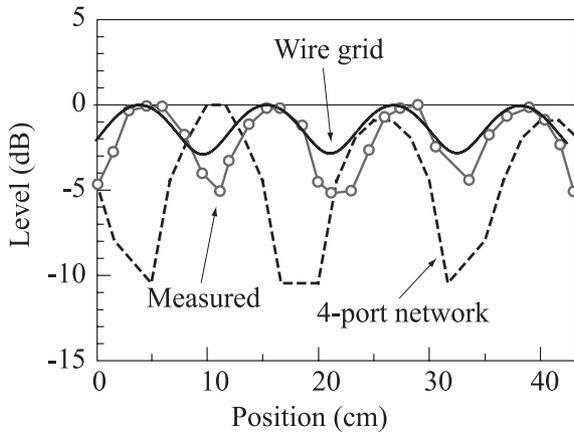
Fig. 10 Current distribution along with cable.

Fig. 11 Experimental set up for measuring the emitted field.

50 Ω. A magnetic field probe, which could operate up to 3 GHz, was connected to a spectrum analyzer and was used to measure the current distribution.

The measured result is shown in Fig. 10. The solid line indicates the calculated value by the moment method using the model in Fig. 2(c), the dotted line indicates the calculated value by the 4-port network method [5], and the line with circles is the measured value. The vertical axis indicates the value normalized by the maximum value. The measurement frequency was 500 MHz, where the 4-port network method could be applied to calculate the radiated electric field [5]. The length of the wire in the model was 1.7 mm and the segment length was the same as the wire length.

This shows that the calculated result by the moment method agrees well with the measured value. On the other hand, the calculated result by the 4-port network method does not agree with the measured value. These results mean that the moment method using the developed wire grid model can be used to calculate the current distribution accurately.

3.3   Radiated Electromagnetic Field

To confirm the validity of the calculation model, the radiated electromagnetic field was measured by the experimental set up shown in Fig. 11.

Measurement was carried out in a semi-anechoic chamber (L=6.2 m, W=7.0 m, H=5.9 m) that had a metal ground plane, and the hybrid couplers were connected to both ends of cable. The radiated electric field strength from the cable was measured concerning with both horizontal and vertical polarization. The distance between the antenna and the cable was 3 m, and the angle toward the antenna was fixed at the position in Fig. 11. The antenna height was changed from 1 m to 4 m above the ground plane, and the maximum value of S_{21} for each polarization was measured using a network analyzer. In this paper, we did not change the angle toward to the antenna because of the problem of the turntable size. Other experiment using a large turntable showed that the radiated field strength changed more than 20 dB in fre-
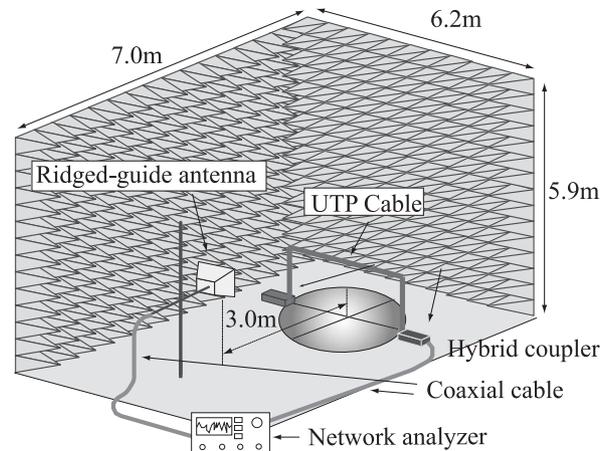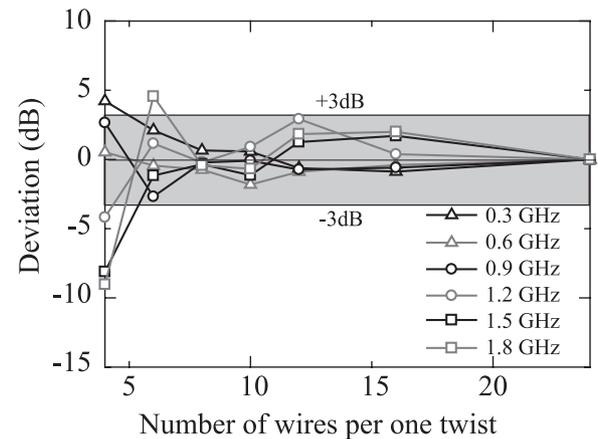
Fig. 12 Relation between the wire length and the calculated field strength.

quency range of 30 MHz to 1000 MHz. The change of the maximum level was lower than the change at the layout in Fig. 11. This means that the comparison at the fixed angle is severer than the comparison of the maximum level when we compare the measured level with the calculated level.

The height of the cable was 0.5 m and the horizontal length was 1.0 m. The input level at the A port of the hybrid coupler was 0 dBm. Measurement frequency ranges were from 0.3 GHz to 2 GHz. A log-periodic antenna was used from 0.3 GHz to 1 GHz and a ridge-guide antenna was used from 1 GHz to 2 GHz. From S_{21} [dB] and the antenna factor, AF [dB], the electric field strength E [dBμV/m] is given by

$$E = V_{in} + AF + S_{21} \tag{4}$$

Where, V_{in} in [dBμV] is the output level of network analyzer that is the same as the input level of the hybrid coupler. The level of voltage sources in Fig. 6 was calculated based on the measured value which is described in Sect. 3.1, and these were used to calculate the radiated electromagnetic field.

The relation between the wire length of the model and the calculated field strength is shown in Fig. 12. Although the calculated results for horizontal polarization are shown
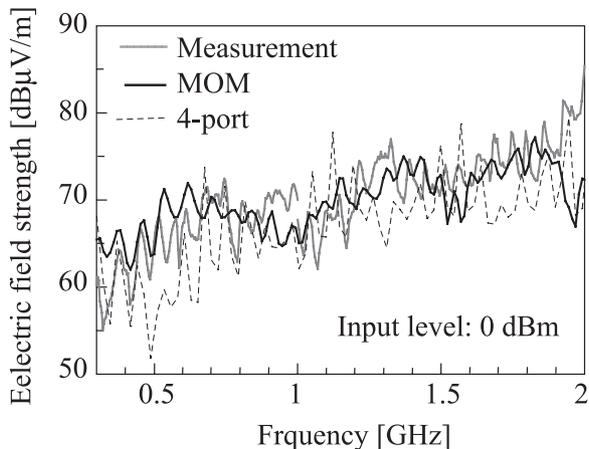
Fig. 13 Calculated and measured field strength for horizontal polarization.
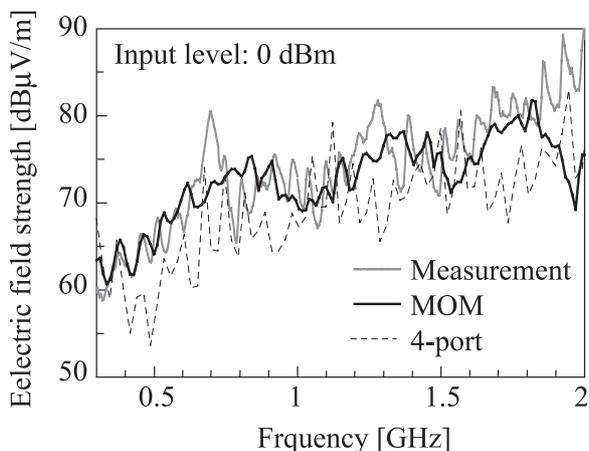
Fig. 14 Calculated and measured field strength for vertical polarization.

in this figure, the similar results are obtained for the vertical polarization.

The vertical axis represents the calculated results of the deviation normalized by the value when the number of wires per one twist is 24. In this paper, we use the number of wires per one twist to present the wire length because the wire model of the UTP cable is constructed with the twist. In this case, the wire length is 0.71 mm. The results in Fig. 12 suggest that the deviation is within 3 dB when the number of wires per one twist is more than 8. Therefore, we use 16 as the number of wires per one twist.

The calculated and measured field strength is shown in Figs. 13 and 14. Figure 13 shows the result for horizontal polarization, and Fig. 14 shows the vertical one. The solid line indicates the calculated results by the moment method using the developed wire grid model shown in Fig. 2(b), the dotted line indicates the calculated results by the 4-port network method [5], and the gray line indicates the measured value.

This shows that the radiated field strength increases in proportion to the increase of frequency. The calculated

value of the moment method almost agrees with the measured one for both horizontal and vertical polarization in frequency rage of less than 1.8 GHz. However, the calculated value of the 4-port network method has the difference from the measured value for vertical polarization compared with the calculated results of the wire grid model. This means that the moment method using the proposed wire grid model is effective to calculate the radiated field from 0.3 MHz to 2 GHz.

The 4-port network method has the advantages that the calculation cost of the method is low, and the radiated field from a long cable can be calculated by the method. Therefore, the method can also be used if we permit some deviations.

The deviation between measured and calculated values increases more than 1.9 GHz. The reason might be the performance limit of the hybrid coupler because the phenomenon does not change when the cable length changes, and the similar phenomenon is obtained from the measurement in the frequency range of 2 GHz to 3 GHz.

4. Conclusion

The transmission speed of the systems using UTP cable increases day by day. The investigation of the electromagnetic field emitted from UTP cable is needed in the frequency rang more than 1 GHz.

The wire grid model was developed to calculate the radiated field by the moment method. The one twisted pair was selected for the calculation, and this is represented by the wire grid model. The radius of conductor was modified to meet the inductance per unit length of the wire grid model by the theory. The capacitance was inserted between wires of the model to meet the capacitance per unit length calculated by FEM.

The current distribution on the line and the radiated electric field strength were calculated by the moment method using the developed wire grid model, and the results were compared with the measured value and with the calculated value by the 4-port network method. The investigation shows that the calculated results by the moment method were almost corresponding to the measured results from 0.3 GHz to 2 GHz, and the calculated results by the 4-port network method have the difference in case of vertical polarization.

The modeling method should be studied for reducing the difference between calculated and measured values in the future.

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