Analysis and Design of Ribbon Cables for High-Speed Digital Applications

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ABSTRACT: Ribbon cables have been widely used as subsystem interconnections in a large number of digital systems, because they can convey numerous bits of a digital signal simultaneously. In this article, finite difference and finite difference time domain (FDTD) methods are used to analyze and optimize the electrostatic analysis design of ribbon cables, and measurements are used to verify the numerical results.

Keywords: ribbon cables; high-speed interconnections; coupling; cross talk

I. INTRODUCTION

With the recent advancements of integrated circuit and digital circuit technologies, digital electronic systems can operate at very high-speeds. The high-speed digital signals cover a very wide frequency spectrum, which is from DC up to hundreds or thousands of MHz. Traditional multiconductor transmission systems in high-speed digital systems are facing the difficulties of insufficient signal-to-crosstalk ratio at high frequency, which are caused by nonnegligible conductor loss and near-end and far-end coupling from adjacent conductors. Recent research of highspeed digital interconnects has been concentrated on the printed traces in IC packages or on printed circuit boards [1–3]. However, multiconductor cables are widely applied to interconnect digital subsystems and CATV or audio to digital interfaces. One of the most widely applied multiconductor cables is ribbon cable, which can convey numerous bits of signal simultaneously. Therefore, the optimization of multiconductor cabling systems will not only ensure the signal purity at higher speed or higher frequency data communications, but will also reduce the design burdens of dynamic ranges in the interface circuits [4–6]. In this article, finite difference electrostatic analysis and finite difference time domain (FDTD) methods are used to analyze ribbon cables. Cross-talk reduction and input impedance stabilization of ribbon cables are achieved by using stripline or coaxial type metalization in this study. The computed numerical results for three ribbon cables configurations are verified by experimental measurements.

II. METHOD OF ANALYSIS

The component under investigation is a 40 stranded-wire conductor, 28 AWG 0.0126 in. (0.032 cm) in diameter, 0.05 in. (0.127 cm) pitch (spacing between the centers of conductors) PVC (\( \varepsilon_r = 3 \)), ribbon cable as shown in Figure 1a. The insulation around the conductors is 0.036 in. (0.091 cm) in diameter. The cable is optimized
using two different types of metalization to change
the field distribution and reduce field couplings.

Figure 1. The cross-section of (a) ribbon cable, (b)
stripline ribbon cable, and (c) coaxial line ribbon cable.

III. NUMERICAL AND
MEASUREMENT RESULTS

The finite difference electrostatic solutions show-
ning the coupled field in a ribbon cable is illus-
trated in Figure 2, where the brighter conductor
is the excited conductor and the dimmer conduc-
tor is the passive coupled conductor. In Figure 1a,
the coupling between excited and passive conduc-
tors of a ribbon cable is about 6 dB. The cou-
pling in the corresponding stripline ribbon cable
is observed as 29 dB (Fig. 2b), and that of a coax-
ial ribbon is 53 dB (Fig. 2c). From Figure 2, the

resistance) connected as a “Y”. This “Y” termina-
tion provides 100 Ω resistive termination for both
common mode and differential mode of a test pair [7]. The top two pins in a “Y” termina-
tion are connected to two conductors of a test pair,
and the bottom pin is connected to the ground of
the network analyzer. S-parameter measurements
are performed for these three different cables.
The test parameters are return loss, insertion loss,
near-end-crosstalk (NEXT), and far-end-crosstalk
(FEXT), which are defined in [7, 8].

The actual dimensions of the ribbon cable
are obtained using an electronic microscope.
Although the cross-section and the dielectric
loading of the conducting wires look uniform to
the human eyes, it is not uniform under the micro-
scope. The circular like cross-sectional areas of
the dielectric and the conductors are translated to
equivalent rectangular areas to facilitate the sim-
ulation procedure using a Cartesian coordinate
system. In both finite difference electrostatic and
FDTD simulations, the ribbon cables are mod-
eled using Cartesian cells such that the rectangular
conductors and surrounding dielectric are equiv-
alent to the circular shape of the actual cables.
The finite difference method is used first to pro-
vide insights about the field coupling between two
adjacent conductors at low frequency. To study
the coupling of a ribbon cable versus frequency,
a dynamic numerical method, the FDTD tech-
nique [9], with perfectly matched layers (PML)
[10], is used. The cell sizes used in this method
are 0.1125 mm for the cross-section and 0.150
mm for the longitudinal length. Due to the lim-
itation of computation resources, the lengths of
ribbon cables are simulated up to 60 mm, and the
transient results are presented for frequencies up
to at least 10 GHz.
coupling between two adjacent conductors is dramatically reduced by using stripline and coaxial metalization.

In many digital transmission systems, differential mode propagation is adopted, such as currently used twisted pairs in cabling systems in local area networks [8], which ensures lower interference from the environments than the 2-wire unbalanced mode. Ribbon cables can also be used to convey differential mode signals. Therefore, measurements of three different types of ribbon cables have been made and are presented.

The transient and spectral analysis of a 50 and 100 MHz digital clock signal usually used in recent designs of computers and electronic equipment are shown in Figures 3a and 3b, respectively. From the frequency spectrum, one notices that

**Figure 2.** The cross-sectional voltage distribution of a section of (a) ribbon cable, (b) stripline ribbon cable, and (c) coaxial line ribbon cable consisting of two adjacent conductors.

**Figure 3.** (a) Transient responses of a 50 and 100 MHz digital clock. (b) Spectrum analyses of a 50 and 100 MHz digital clock.
the analysis of ribbon cables should be conducted to at least 500 MHz, which may encompass the major frequency spectrum of a 100 MHz digital clock as shown in Figure 3b.

The S-parameter measurements of the three cables of this study are plotted in Figure 4. From the return loss levels plotted in Figure 4a, the return loss of the bare ribbon cable is not as good as the other two proposed designs of ribbon cables for 100 Ω system. This bare ribbon cable is designed for 100 Ω characteristic impedance, but the test results show the significant deviation from its nominal impedance. The patterns of return losses should be symmetrical at odd multiple of quarter-wavelength and repetitive at odd multiple of half-wavelength. However, patterns are slightly distorted and the nulls of the three cables are also not in the correct order. The frequency of the nulls in the return loss of bare ribbon cable should be the highest among the three cables due to its faster propagation speed and longer wavelength. Therefore, the loading effects of the 5-cm
The test lead deembedding for the original S-parameter measurements is accomplished using the 2-port deembedding model in Agilent advanced design system (ADS) [11]. To adopt this ADS deembedding model, S-parameters of the test leads are required. However, to measure a 5-cm test lead is difficult due to its short electrical length. Therefore, a 30-cm test lead is measured and modeled to obtain an ADS model with scalable length. The measurements for a 30-cm test lead are shown in Figure 5. The characteristic impedance of the 30-cm test lead is obtained by applying

\[ Z_o = \sqrt{Z_{is}Z_{io}}, \]  

where the \( Z_{is} \) and \( Z_{io} \) are the input impedance with one end short-circuited and open-circuited, respectively. The 2-port S-parameter is renormalized with the real part of this extracted \( Z_o \), thus, the true attenuation and phase delay of this cable are obtained. Using this phase delay, the frequency dependent propagation speed \( (V'_p) \) and effective dielectric constant \( (\varepsilon_{\text{eff}}) \) can be obtained using

\[ V'_p(\omega) = l / \left( -\frac{\partial \phi}{\partial \omega} \right), \]  

\[ \varepsilon_{\text{eff}}(\omega) = \left( c/V'_p(\omega) \right)^2, \]  

where \( l \) is the physical length of a transmission line, \( \phi \) is the transmission phase change after renormalization, and \( c \) is the speed of light. The characteristic impedance of the test lead is 174 \( \Omega \) at low frequency and increases up to 180 \( \Omega \) at 500 MHz. By applying the extracted \( Z_o \) and \( \varepsilon_{\text{eff}} \) in the ADS physical transmission line model, the test simulation model is developed. The effectiveness of this ADS model is examined in Figure 5, which shows excellent agreement between the measurements and the simulations. The 5-cm test leads are obtained by scaling the length of this ADS model.

If the ADS deembedding model is applied to the measured data in Figure 4, the deembedded measurements are plotted in Figure 6, which show the correct order of the nulls in the return losses. From Figure 6a, the return loss of strip ribbon cable is better than 20 dB up to 450 MHz, so this cable can be considered a very good 100 \( \Omega \) transmission line. On the contrary, the return loss of the bare ribbon cable at multiple of quarter wavelength is less than 10 dB due to its dispersive characteristic impedance. By applying eq. (1) with passive pairs terminated with 100 \( \Omega \) reference impedance, the characteristic impedances of these three cables are obtained. The characteristic impedance of bare ribbon cable is 160 \( \Omega \) at low frequency and deviates up to 190 \( \Omega \) at 500 MHz. The characteristic impedance of the strip ribbon and coax ribbon are 94 \( \Omega \) and 80 \( \Omega \) at low frequencies and increases to 110 \( \Omega \) and 90 \( \Omega \) at 500 MHz, respectively. From Figure 6a, the return loss of the
coax ribbon cable becomes more than 20 dB after 300 MHz, which can be explained by its increase of characteristic impedance toward 90 Ω at higher frequency. Both deembedded NEXT and FEXT shown in Figures 6c and d are similar to those in Figures 4c and d, because the cross talks are determined by the mutual equivalent capacitance and inductance between conductors.

Applying the characteristic impedance derived in the previous section in the port reference impedance of ADS, the renormalization of these measured data can be achieved. The port reference impedance in ADS allows only real numbers, so the renormalization is based on the real part of the characteristic impedance. The return losses after renormalizations shown in Figure 7a are improved significantly compared with those in Figures 4a and 6a. The ripples in insertion losses in Figure 7b are also reduced significantly compared with those in Figures 4b and 6b. This

Figure 6. De-embedded measurements of three different ribbon cables: (a) return loss, (b) insertion loss, (c) NEXT loss, and (d) FEXT loss.
Renormalized measurements of three different ribbon cables: (a) Return loss, (b) insertion loss, (c) NEXT loss, and (d) FEXT loss.

Renormalized insertion loss should approximate the conduction losses of the transmission line. The imperfections in renormalizations are caused by only matching the transmission line with its real-part characteristic impedance. The repetitive patterns of NEXT in Figure 7c are similar to those of the coupled lines with different spacing. The NEXT levels before 400 MHz are 20, 30, and 40 dB for bare ribbon, strip ribbon, and coax ribbon cables, respectively, which is similar to those in Figure 4c. The FEXT levels of strip and coax ribbon cables also show improvement over the bare ribbon cable shown in Figure 7d. The advantages of the stripline and coaxial types of metalization are obvious in yielding less dispersive characteristic impedance and lower cross-talk. By either increasing the thickness of dielectric insulator or decreasing the thickness of the conductors slightly, a 100 Ω characteristic impedance coax ribbon cable can be achieved.

To compare the measurements with the FDTD simulation results, the length difference between
the two methods (90 cm in measurement and 6 cm in FDTD) needs to be resolved. In addition, the cable conductors are stranded wires, which have higher attenuation than the solid wire models in FDTD simulations. These lengths determine both cable attenuation and the repeatability of all test parameters of finite length transmission lines. Therefore, two test parameters, attenuation to crosstalk ratio (ACR) and equal-level far-end cross-talk (EL-FEXT) are adopted to remove the length variations, which are defined in [7, 8] and are very commonly used in cabling industry. The ACR is defined as the ratio of the insertion loss to NEXT, and EL-FEXT is defined as the ratio of the insertion loss to FEXT. These parameters are the signal to NEXT and FEXT ratios. Instead of plotting the test parameters versus frequency, the test parameters are analyzed versus its electrical length, defined as the physical length normalized with the corresponding guiding wavelength at each frequency. The guided wavelength ($\lambda_g$) is defined as

$$\lambda_g = \frac{V_p}{\omega f}. \quad (4)$$

For a finite uniform transmission line, the maximum and minimum of its return loss are located where the physical length is equal to odd multiples and even multiples of $\lambda_g/4$, respectively. Applying eq. (4) and the parameters ACR and EL-FEXT, results from the FDTD analysis and the measurements can be compared correctly. The comparison using normalized length is analogous to the analysis of wire antennas using normalized antenna length.

The FDTD analysis of stripline ribbon cable is shown in Figure 8. The ACR of stripline ribbon was plotted in Figure 8a, where good agreement between the results of FDTD and measurements are found. In Figure 8, the ACR at 2.5 wavelength is equal to the ACR of the 90-cm ribbon cable at 450 MHz. The measured ACR and EL-FEXT deviate from the computed values as the frequency increases which is possibly caused by the small air-gaps between metalization layers and cable. To verify this point, 0.1125-mm air-gaps between the metalization layers and the ribbon cable are introduced in the FDTD simulation. From Figures 8a and 8b, the simulated results of the air-gaped strip ribbon show a significant degradation in FEXT but slight degradation in NEXT, which encompass the measured results. If the metalization is attached to the ribbon cables very tightly, both ACR and EL-FEXT agree with the FDTD analysis. Therefore, decoupling of 35 dB ACR and 37 dB EL-FEXT levels can be expected when the length is less than 2.5 wavelength.

The ACR and EL-FEXT of coaxial ribbon cable obtained from FDTD analysis and measurements are shown in Figure 9. We are also interpreting that the differences between measured and computed data for the coaxial cable are due to the air-gaps. To prove this point, we simulated
the air-gap in the computational algorithm and have obtained the results that closely agree with the measurements as shown in Figure 9. The measurements agree with the FDTD simulation with 0.225-mm air-gaps, as shown in Figure 9. Therefore, when metalization completely fills the gaps between conductors and tightly attached to the top and bottom ribbon cable surfaces, decoupling of 73 dB ACR and 76 dB of EL-FEXT levels can be achieved with less than 2.5 wavelength. These signal-to-crosstalk performances are electrically effective for parallel multicoaxial cables.

In recent digital–analog interfaces, miniature ribbon coaxial cables are used [5], which can also be found in CATV-to-digital or audio-to-digital interface circuitry. Instead of using miniature parallel coaxial cables, coaxially metalized ribbon cable can be an effective replacement with low design profiles and costs. In addition, the coaxially metalized ribbon cables can be used to support future higher speed digital systems very effectively, when the characteristic impedance is adjusted to the nominal impedance of the digital system by increasing or decreasing the thickness of dielectric insulation.

Therefore, when the cable length is less than 2.5 wavelength, bare ribbon cables can only ensure decoupling levels of 12 dB ACR and 10 dB EL-FEXT. However, the ACR and EL-FEXT for the stripline and coaxial ribbon cables are at least 35 and 37 dB and 73 and 76, respectively.

IV. CONCLUSIONS

High-speed ribbon cables can be achieved by applying stripline or coaxial metalization, which not only provides better-controlled characteristic impedance than traditional bare ribbon cables, but also results in higher signal-to-crosstalk ratios. Multiple parallel miniature coaxial cables can be achieved by simply metalizing the top and bottom surfaces of ordinary ribbon cable, which dramatically reduces the manufacturing costs and efforts while improving cable performance.

REFERENCES

5. L. Danne, Make reliable interconnections in rugged, high-speed applications, Electr Des 47(9) 85–90.
7. Additional Transmission Performance Specification for 100 Ω 4-Pair CAT 5e Cabling, Draft 11, April 9, 1999, ANSI/TIA/EIA.

BIOGRAPHIES

Chun-Wen Pan Huang was born in Taipei, Taiwan, R.O.C., on October 18, 1967. He received the diploma in electronic engineering from the National Taipei Institute of Technology, Taipei, Taiwan, in May 1991. From 1991 to 1993, he served as an army officer in charge of wire and wireless telecommunication systems and technologies at Kaohsiung Regimen Control Area command, Kaohsiung, Taiwan, R.O.C. He started his graduate study at the electrical engineering department of the University of Mississippi in August 1994, and received the M.S. and Ph.D. degrees in May 1996 and December 1999, respectively. From May 1998 to March 2000, he was with Thomas and Betts Corporation in Memphis, TN, for the analysis and designs of high-speed digital and passive RF devices and subsystems. In March 2000, he joined Anadigics, Inc. in Warren, New Jersey, where he is responsible for the characterizations and designs for the interconnections and passives in RF/Microwave integrated circuits and multiple chip modules (MCM). His research interests are in the analysis and design of RF/Microwave circuits and high-speed digital devices, and the applications of numerical methods for solving electromagnetic problems. Dr. Huang has published more than 20 technical papers and presentations.

Atef Z. Elsherbeni received an honor B.Sc. degree in electronics and communications, an honor B.Sc. degree in applied physics, and an M.Eng. degree in electrical engineering, all from Cairo University, Cairo, Egypt, in 1976, 1979, and 1982, respectively, and a Ph.D. degree in electrical engineering from Manitoba University, Winnipeg, Manitoba, Canada, in 1987. He was a research assistant with the Faculty of Engineering at Cairo University from 1976 to 1982, and from 1983 to 1986 at the Electrical Engineering Department, Manitoba University. He was a part-time Software and System Design Engineer from March 1980 to December 1982 at the Automated Data System Center, Cairo, Egypt. From January to August 1987, he was a Post Doctoral Fellow at Manitoba University. He joined the faculty at the University of Mississippi in August 1987 as an Assistant Professor of Electrical Engineering. He advanced to the rank of Associate Professor in July 1991, and to the rank of Professor in July 1997. He spent his first sabbatical term in 1996 at the Electrical Engineering Department, University of California at Los Angeles (UCLA). He received the 2001 Applied Computational Electromagnetic Society (ACES) Exemplary Service Award for leadership and contributions as electronic publishing managing editor 1999–2001, the 2001 Researcher/Scholar of the year award in the Department of Electrical Engineering, The University of Mississippi, and the 1996 Outstanding Engineering Educator of the IEEE Memphis Section. His professional interests include scattering and diffraction of electromagnetic waves, numerical techniques, antennas, remote sensing, and computer applications for electromagnetic education. He has published 55 technical journal articles and 12 book chapters on applied electromagnetics, antenna design, and microwave subjects, and presented over 160 papers at professional conferences. Dr. Elsherbeni is a senior member of the Institute of Electrical and Electronics Engineers (IEEE). He is the editor in chief for the Applied Computational Electromagnetic Society (ACES) Journal and the electronic publishing managing editor of ACES. His honorary memberships include the Electromagnetics Academy and the Scientific Sigma Xi Society. He serves on the editorial board of the Book Series on Progress in Electromagnetic Research, the Electromagnetic Waves and Applications Journal, and the Computer Applications in Engineering Education Journal. He is the Chairman of the Educational Activity Committee for the IEEE Region 3 Section. His home page can be found at http://www.ee.olemiss.edu/~atef.

Charles E. Smith was born in Clayton, AL on June 8, 1934. He received the B.E.E., M.S. and Ph.D. degrees from Auburn University, Auburn, AL, in 1959, 1963, and 1968, respectively. While pursuing his advanced degrees from 1959 to 1968, he was employed as a Research Assistant with Auburn University Research Foundation. In late 1968, he accepted the position of Assistant Professor of Electrical Engineering with The University of Mississippi, University, MS, and he advanced to
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