High Electromagnetic Shielding of a 2.5-Gbps Plastic Transceiver Module Using Dispersive Multiwall Carbon Nanotubes

Chia-Ming Chang, Jin-Chen Chiu, Yi-Fen Lan, Jhe-Wei Lin, Chao-Yung Yeh, Wern-Shiarng Jou,
Jiang-Jen Lin, and Wood-Hi Cheng, *Senior Member, IEEE, Member, OSA*

Abstract—**A novel polyimide film, consisting of finely dispersed multiwall carbon nanotubes (MWCNTs) in an ionic liquid (IL), is demonstrated to be high shielding effectiveness (SE) for use in packaging a 2.5-Gbps plastic transceiver module. The IL-dispersed MWCNT composite exhibits a high SE of 40 $\sim$ 46 dB. By comparison, the composite fabricated by nondispersive process requires a higher loading of MWCNTs at 50 wt-% than the IL-dispersed process at only 30 wt-%. The electromagnetic susceptibility (EMS) performance is experimentally evaluated by the eye diagram and bit-error-rate for a 2.5-Gbps lightwave transmission system. The package housing fabricated by the dispersive MWCNT composites shows an enhanced EMS performance, an improved mask margin, and a lower-power penalty. These results indicate that the IL-dispersed MWCNT composites are suitable for packaging low-cost and high-performance optical transceiver modules used in the fiber to the home lightwave transmission systems.**

Index Terms—**Electromagnetic interference (EMI), electromagnetic susceptibility (EMS), ionic liquid (IL) dispersive multiwall carbon nanotubes (MWCNT), plastic optical transceiver modules, shielding effectiveness (SE).**

I. INTRODUCTION

THE electromagnetic susceptibility (EMS) or electromagnetic (EM) immunity of the optical transceiver modules to the electromagnetic interference (EMI) is one of the major concerns to maintain good signal quality of over gigabit transmission rate [1]–[3]. Designing a high EM shielding package/housing is desirable to improve the EMI and EMS performance of the optical transceiver modules. It is well known that metallic package may provide an excellent shielding effectiveness (SE). However, the characteristics of low cost and ease manufacturing have promoted the plastic composite package as the most suitable material for fabricating the optical transceiver modules for using in the fiber to the home (FTTH) applications [3]–[8].

Plastics are inherently transparent to EM radiation and provide no shielding effect against radiation emissions. In order to improve the EM shielding for the plastic packaging, electronic conductive materials have to be blended into the plastic hosts to gain an adequate EM shielding property. Multiwall carbon nanotubes (MWCNTs) may be considered as one of the electronic conductive fillers because of their known properties of high electrical conductivity, nanoscale diameter, high aspect ratio, and possibly strengthened mechanical properties [9], [10]. The aspect ratio of most MWCNTs is higher than 1000, which offers an intensive interconnection in the MWCNT/plastic networks, in resulting a high EM shielding. Recently, the MWCNTs have been the focus of considerable research and development for uses in nanoscale electronic and optoelectronic applications, such as integrated circuit (IC) interconnections [11], optical emission devices [12], and optical transceiver modules [7], [8].

However, the high aspect ratio and low ionic character of MWCNTs are not easily dispersed within the plastic hosts. The lack of dispersing ability in the polymer matrices is caused by internal van der Waals force among the MWCNTs and their consequent aggregation [13]–[18]. Without a fine dispersion, the MWCNTs may form local clusters and poor homogeneity existed in the MWCNT composite. As a consequence, the weight percentage of the added MWCNTs is required in order to achieve a good electrical conductivity and a comparable SE. For developing a cost effective material, a fine dispersion of MWCNTs in the polymer matrices is essential.

In this study, we present an EM shielding performance for a plastic composite by employing polyimide (PI)-based dispersive MWCNTs. The MWCNT-PI films are prepared by using a physical dispersive method of dispersing MWCNTs into PI resin and thin films. The MWCNT-PI composites are then formed by several stacked thin films. The resultant package of the film composites with 30% weight percentage MWCNTs exhibits high SE of 40 $\sim$ 46 dB in the far-field source. In addition, the package housing fabricated by dispersive MWCNT composites shows an enhanced EMS performance, an improved mask margin, and a lower power penalty for a 2.5-Gbps lightwave transmission system. The IL-dispersed MWCNT composites are proven to be suitable for packaging low-cost and high-performance optical transceiver modules for use in the FTTH lightwave transmission systems.

Manuscript received June 19, 2007; revised December 22, 2007. This work was supported in part by the MOP Program for Promoting Academic Excellence of University, R.O.C., under Grant A-91-E-FA08-1-4.

C.-M. Chang, J.-C. Chiu, J.-W. Lin, and W.-H. Cheng are with Institute of Electro-Optical Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C. (e-mail: d9135805@student.nsysu.edu.tw; c.m.chang@nxp.com; jamescm.chang@msa.hinet.net; m933050043@student.nsysu.edu.tw; jooj1213@yahoo.com.tw; whcheng@mail.nsysu.edu.tw).

Y.-F. Lan and J.-J. Lin are with Institute of Polymer Science and Engineering, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: d95549006@ntu.edu.tw; jianglin@ntu.edu.tw).

C.-Y. Yeh is with Metal Industries Research and Development Center, Kaohsiung, Taiwan, R.O.C. (e-mail: chaoyeh@yahoo.com).

W.-S. Jou is with the Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan, R.O.C. (e-mail: wsjou@cc.kuas.edu.tw).

Digital Object Identifier 10.1109/JLT.2008.917054

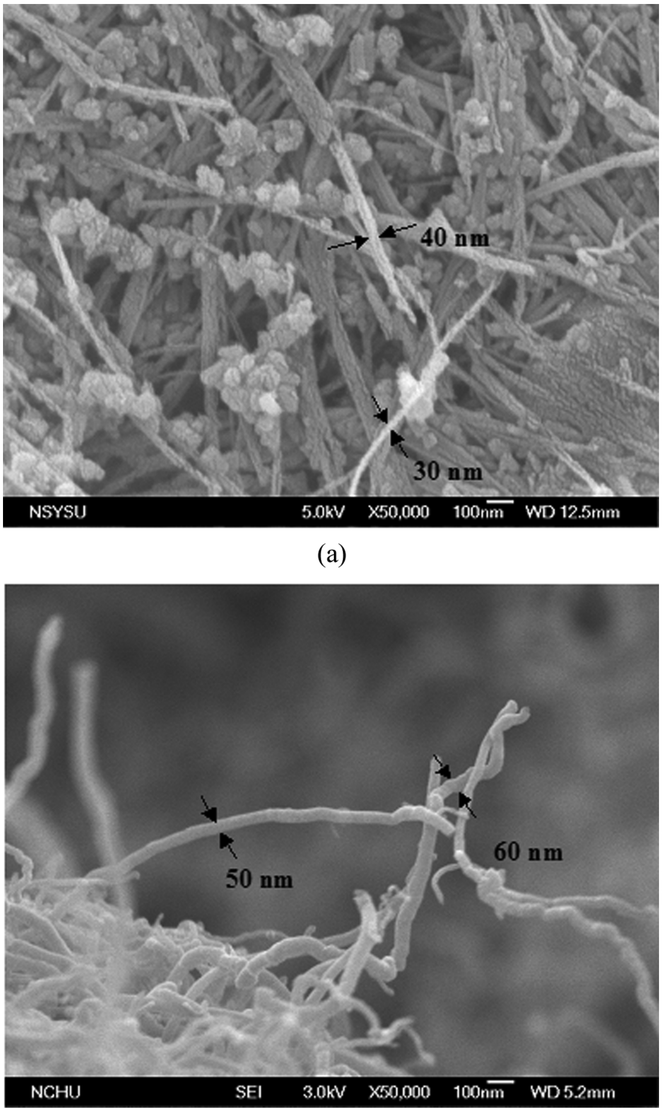
II. FABRICATION OF MWCNT COMPOSITES

A. Dispersion of Multiwwalled Carbon Nanotubes (MWCNTs)

MWCNTs are commercially available from the methods of ADM [19] or CVD. The aspect ratio of these MWCNTs is about 500 under SEM observation. The MWCNTs produced by ADM have a needle-like shape, as shown in Fig. 1(a), not like those produced by CVD, as shown in Fig. 1(b). Usually, CVD produced carbon nanotubes are 95% pure and 50 $\sim$ 60 nm in diameter and 0.5 $\sim$ 10 μm in length. Although the raw MWCNTs could be built into conductive networks in a composite, the lack of the homogeneous dispersion of MWCNTs in the matrices is problematic for achieving in high-performance composites. To avoid the generally serious MWCNTs self-aggregation and to improve the inorganic-organic network adhesions are two key issues for determining their reinforcement effects. MWCNTs have a strong tendency for aggregation and their difficulty to disperse in either water or any organic solvents due to the inherent van der Waals attractions among MWCNTs [13]–[18]. In literature, it has been reveled that the carbon nanotubles may be dispersed by the methods of chemical modification and physical adhesions [20]–[22]. The chemical modification requires a treatment of acids, such as HNO_3, and H_2SO_4, which may adversely damage the MWCNT structure, inevitably requires a great deal of surfactant addition in the adhesion process [20].

In this study, we adopt the physical method for dispersing the MWCNTs in ionic liquid (IL) dispersants [21], [22]. The method involves an intensive grinding of the mixture of IL and MWCNTs and followed by dissolving into N-methylpyrrolidone (NMP) solvent. The van der Waals force and $\pi - \pi$ stacking interactions between the MWCNTs were mitigated by the mixing with the imidazolium ions in the MWCNT-IL hybrid solution [21]. The dispersion was efficiently reinforced by taking advantage of a strong affinity of the imidazolium cation ion toward the π-electronic MWCNT surface. The dispersion mechanism in this work is that the organic cations of the IL potentially interact with π-electronic compounds through so-called "cation-π" interaction [21].

The examination using an UV-vis spectrometer has evidenced the uniformity of the MWCNT-IL suspension at the absorption of 550-nm light. Fig. 2 shows the absorption of various weight ratios of MWCNT-IL dispersions in the NMP. It was found that the MWCNTs from CVD were easier to be dispersed than that from ADM method. The difference is perhaps reflecting their impurities that are contaminated from the manufacturing. The MWCNTs from the CVD method are 95% pure; whereas the ADM method generates MWCNTs with less purity. The impurities include carbon nano capsules (CNC), carbonaceous impurities or ash, and amorphous carbon [7]. In our experiments, it requires more IL amount for dispersing the ADM produced MWCNTs. To fabricate the MWCNT-PI composite, a poly (amic acid) resin precursor (PAA) was allowed to mix with the finely dispersed MWCNT-IL suspension at the MWCNT weigh percentage of 0.1 $\sim$ 30%. After the vigorous mixing, the slurry was casted onto a glass substrate and cured into MWCNT-PI composite films. In Fig. 3, a SEM micrograph of MWCNT-PI composite is shown for the fine dispersion of MWCNT embedded in the PI matrices.



(a)

(b)

Fig. 1. (a) MWCNTs (ADM); (b) MWCNTs (CVD).

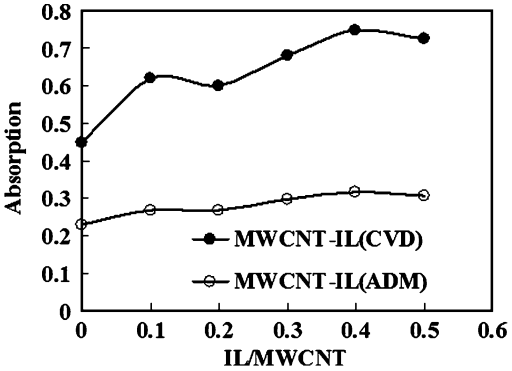


Fig. 2. UV-vis spectrometer absorption of various weight ratios of MWCNT-IL hybrid dispersed in NMP solvent at wavelength of 550 nm.

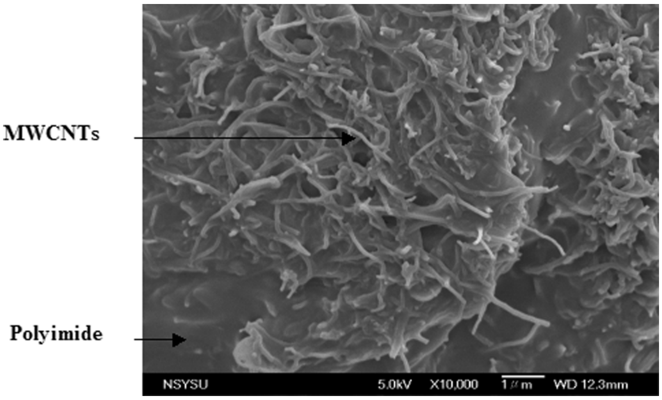


Fig. 3. SEM photo of MWCNT-PI composite.

B. Fabrication of MWCNT-Polyimide (PI) Composites

According to the basic EM shielding theory, the SE increases as the material conductivity increases [7], [8]. The more MWCNT material is added, the more overlapping conductive MWCNT networking, and, hence, the higher conductivity and the higher SE are expected. The conductivity of the MWCNT-PI composite was measured by a four-terminal technique. Fig. 4 shows the relations between weight percentage of MWCNTs and electrical conductivity. The measured electrical conductivity for the IL-dispersed MWCNT-PI composite in Fig. 4(a) is compared to the nondispersed MWCNT-LCP composite in Fig. 4(b) [7], [8]. These comparisons indicate the effectiveness for dispersing higher contents of MWCNTs in order to increase electrical conductivity. The finely dispersed MWCNT composites have demonstrated a remarkable improvement in comparing to our previous reported [7], [8] and comparable to the results reported by Kim [23], [24]. It is clearly indicates that the fine dispersion of MWCNTs is the predominating factor for fabricating the higher conductive materials.

III. SHIELDING EFFECTIVENESS MEASUREMENT

A. Shielding Effectiveness of MWCNT-PI Composite

The SE of the MWCNT-PI composite is measured by the ASTM D4935-92 method [25]. In Fig. 5, the SE for a dispersed MWCNT-PI in 850 μm thickness (30% weight percentage) and nondispersed MWCNT-LCP in 1200 μm thickness (30% and 50% weight percentages) are compared. The SE results are higher than 40 dB under the frequency range between 1 and 3 GHz for the 30% weight percentage MWCNT-PI and the comparable 50% weight percentage MWCNT-LCP. The result indicates that the lower weight content of the dispersed MWCNT-PI can achieve a higher SE. This implies a low cost of MWCNT composites can be used to build the EMI shielding module box of optical transceiver. According to the shielding theory, a shielding effect is generally dependent on the increase of electrical conductivity and film thickness. With the higher electrical conductivity but a thinner film, the dispersed MWCNT-PI (850 μm) was found to have a comparable SE than that of the nondispersed MWCNT-LCP (1200 μm).

B. SE of MWCNT-PI Module Box

The SE of the module box is measured by using a near field method. A monopole type antenna, used as the radiant source, was built into a module box of the MWCNT-PI composite in order to measure the difference of reference level and shielding level. The packaged radiation source is closer to the shielding walls, and nearer to the situation of practical applications. By adopting the setup of the FCC class B, the distance between the receiver antenna and the shielding box was 3 m. This is a near field measurement since the distance between radiation source (packaged in a shield box) and shield material (walls of shield box) was less than $\lambda/2\pi$ (where λ is the wavelength). The wave impedance in the near field measurements is function of distance, rather than a constant for the far field. In our measurements, the wavelength was 12 cm operating at 2.5 Gbps and the distance between the packaged radiation source and the shield wall was less than 2 cm. This falls into the near field conditions. The SE measurement in a near field source was performed in a fully anechoic electromagnetic compatibility (EMC) chamber [3], [6], [7]. Because the hybrid absorbers combining the ferrite tiles and foam absorbers were aligned on the metal-shielded wall inside the chamber, good wave-absorbing performance could be achieved from 30 MHz to 18 GHz for the EMC chamber. The radiation source was put on a wooden table from which an antenna was seated at a distance of 3 m for receiving the radiated field. An electric monopole with a 2-cm length was used to emulate the radiation energy inside the molded housing.

In Fig. 6(a), the received radiation under the situations of with and without shielding boxes is shown to be 62 dBμV/m and 95 dBμV/m on average, respectively. Fig. 6(b) shows the result of the SE behavior versus frequency. The SE of the MWCNT-PI composites was measured from 20 to 37 dB in the frequency range of 1 to 3 GHz.

IV. EMS PERFORMANCE

A. EMS Performance of an MWCNT-PI Packaged 2.5 Gb/s Optical Receiver

Fig. 7 shows a setup for measuring the performance for a 2.5-Gbps optical receiver. The dimension of the package box is $3 \times 4 \times 5.5$ cm^3 and the thickness of the wall is 850 μm. Two drilled holes in one sidewall of the package box were used to mount the connectors for two coaxial cables to transmit the electrical data in differential pair. Another sidewall was drilled one hole for the optical receptacle. A pattern generator (HP 70841B) was used to transmit 2.5-Gbps signal to the optical receiver module under test through an optical transmitter. The $2^{31} - 1$ pseudo-random bit sequence (PRBS) pattern is given by the pattern generator. The received signal is electrically returned to an error detector (HP 70842B) and the eye patterns can also be measured by a digital communication analyzer (HP83480A). To perform the EMS measurement of the packaged optical receiver, the monopole radiator excited by the pattern generator is used to interfere with the packed module at a distance of 4 cm.

Fig. 8 shows the eye-diagrams of a 2.5-Gbps optical receiver in absence and presence of MWCNT-PI shield in box under an interference of monopole voltage amplitude 2 Vpp. The transmission speed is 2.5 Gbps and the used mask is OC-48. The eye

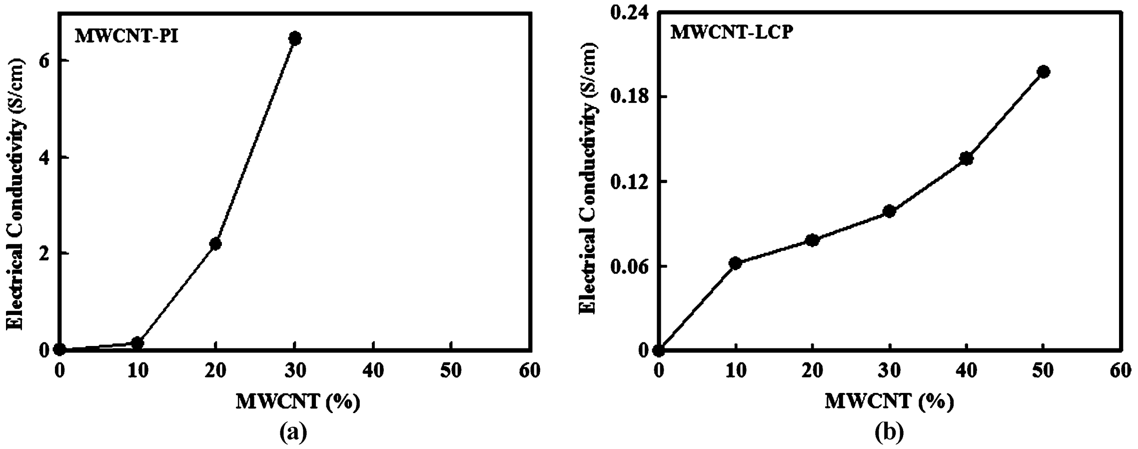


Fig. 4. Relation between MWCNT weight percentage and electrical conductivity of (a) IL dispersed MWCNT-PI composite and (b) MWCNT-LCP composite.

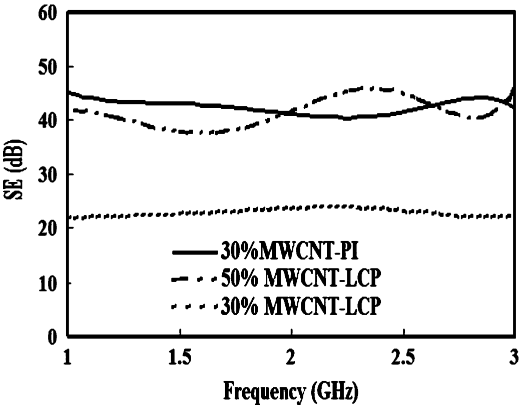


Fig. 5. SE of dispersed 30 wt% MWCNT-PI, 50 wt%, and 30 wt% MWCNT-LCP.

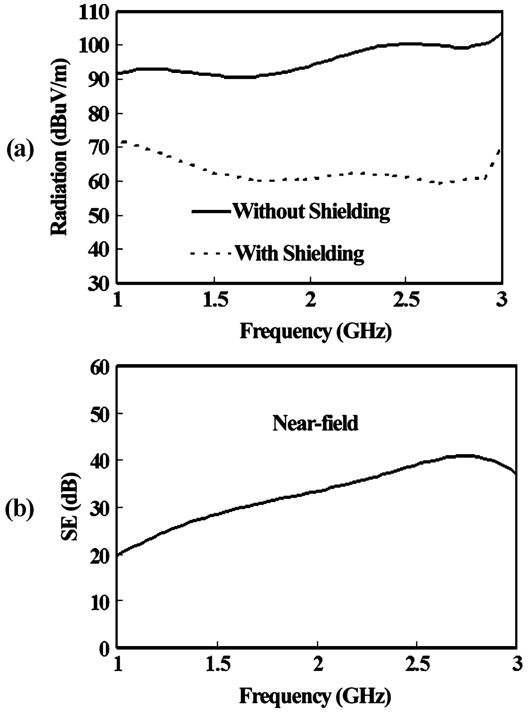


Fig. 6. (a) Received radiations and (b) near-field SE of monotype antenna enclosed in a 30 wt% MWCNT-PI box.

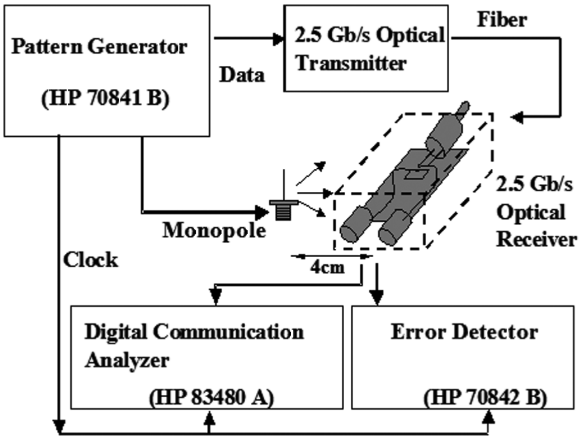


Fig. 7. Setup for receiver performance measurement.

of with shielding box is apparently more open than that in the absence of a shielding. The mask margin is improved from 43% to 56% in the presence of MWCNT-PI shielding. Fig. 9 shows the mask margins of with and without shielding under different interference voltage amplitudes of the monopole type antenna. An enhancement of 13% with shielding box was achieved.

The EMS performance of the proposed package is demonstrated by the measurement of the bit-error-rate (BER) tests. Fig. 10 shows the BER measurement for three different situations. Case A is the unpackaged module with a radiated interference; Case B is the packaged module with a radiated interference; and Case C is the unpackaged module without a radiated interference. As shown in Fig. 10, the received optical power is about -16.5 dBm and -18 dBm for cases A and B, respectively, in achieving the BER of 10^{-12}. Comparing with the cases A and B with strongly radiated noise, the optical power of packaged module can be reduced about 1.5 dBm. Therefore, the optical module fabricated by the IL-dispersed MWCNT-PI composites significantly increases the EM immunity to the radiated interference. Fig. 10 showed the bending of the line in BER 10^{-12} for unpackaged module without radiated interference (case C) and the unbending line in BER 10^{-12} for packaged module with radiated interference (case B). The box not only shielded the intended interference source but also shielded the background noise from the ambient environment.

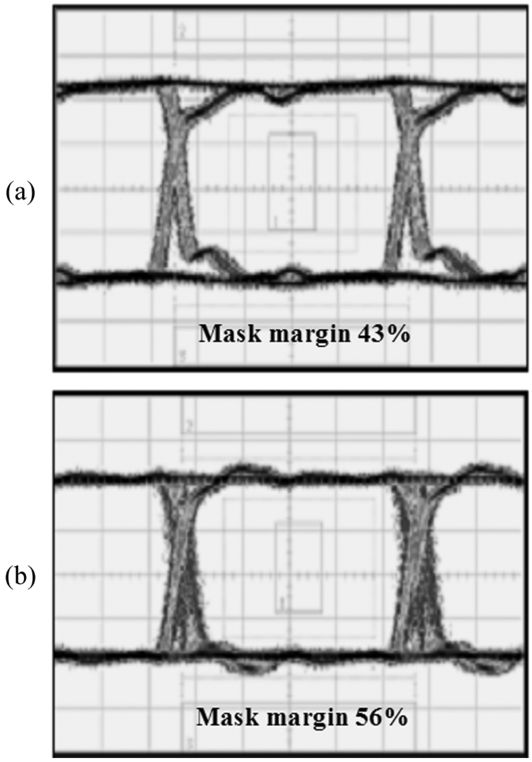


Fig. 8. Eye-diagrams of 2.5 Gb/s optical receiver (a) without shield and (b) with shield.

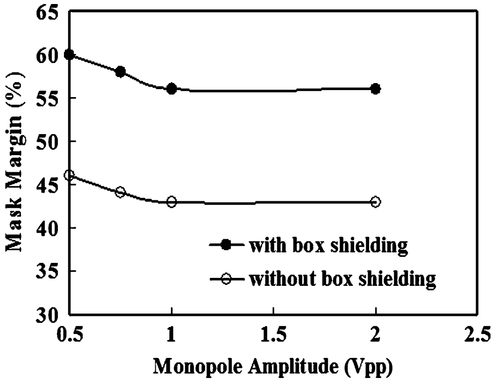


Fig. 9. Mask margins of with shield and without shield optical receiver under different interference voltage amplitudes of a monopole type antenna.

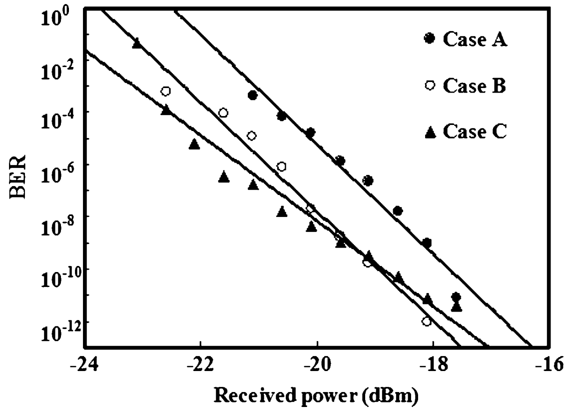


Fig. 10. BER versus the received optical power for three different cases. Case A (unpackaged module with radiated interference), Case B (packaged module with radiated interference), and Case C (unpackaged module without radiated interference).

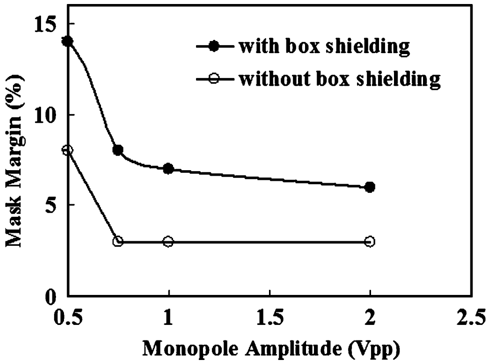


Fig. 11. Mask margins of with shield and without shield optical transmitter under different interference voltage amplitudes of a monopole type antenna.

B. EMS Performance of an MWCNT-PI Packaged 2.5-Gbps Optical Transmitter

In order to measure the performance of a 2.5-Gbps optical transmitter, a pattern generator (HP 70841B) was used to transmit 2.5-Gbps electrical signal to the optical transmitter module. The output optical signal of the optical transmitter is fed into a digital communication analyzer (HP83480A). For the EMS measurement of the packaged optical transmitter, the monopole radiator excited by the pattern generator is also used to interfere with the packaged module at a distance of 4 cm. Fig. 11 shows the mask margins with and without shielding box under different interference voltage amplitudes of the monopole type antenna. There observed approximately a 5% enhancement with shielding box. The mask margin for a 2.5-Gbps optical transmitter under an interference of monopole voltage amplitude of 0.75 Vpp was improved from 3% to 8% with packaged box of the MWCNT-PI composites.

The mask margin with box shielding was higher than that without box shielding even at zero monopole amplitude. This was due to the box shielding onto the electronic circuit components inside the box and the other nonintended interference from the ambient electronic facility in the surrounding. In Fig. 9, it was shown a larger mask margin difference than in Fig. 11. The mask margin was related to the performance of the electronic circuit under test. The optical receiver under test performed a better mask margin than transmitter. For the internal signal noise of the optical modules, there is the energy coupling between the electronic circuit components inside the shielding box. For the EMS test, the intended radiation source (monopole type antenna) is out of the box. With and without the shielding box, the level of the internal signal noise inside the optical module should be the same. However, the changes of the mask margin in Figs. 9 and 11 were caused by the external radiation source.

V. CONCLUSION

A novel polyimide film material, consisting of finely dispersed MWCNTs, was developed for uses in packaging a 2.5-Gbps plastic transceiver module. The results showed that the IL-dispersed MWCNT composites with 30% weight percentage MWCNTs exhibited high SE of 40 ~ 46 dB. By comparison, the previous works on MWCNT composites fabricated by nondispersive process required a higher weight percentage (50%) of MWCNTs [7], [8]. Furthermore, the IL-dispersed MWCNT composite offers a high electrical conductivity and effective SE with a low loading of MWCNTs. The newly developed package housing, fabricated by IL-dispersed MWCNT composites, clearly improved EMS performance, mask margin, and power penalty for a 2.5-Gbps lightwave transmission system. This significantly improved result has marked the achievement of using the dispersive MWCNT composites for the high SE and suitability for packaging low-cost and high-performance optical transceiver modules used in the FTTH lightwave transmission systems.

REFERENCES

[1] J. T. DiBene and J. L. Knighten, "Effects of device variations on the EMI potential of high speed digital integrated circuits," *IEEE Electromagn. Compat.*, vol. 39, no. 4, pp. 208–212, Aug. 1997.

[2] D. M. Hockanson, X. Ye, J. L. Drewniak, T. H. Hubing, T. P. V. Doren, and R. E. DuBroff, "FDTD and experimental investigation of EMI from stacked-card PCB configurations," *IEEE Trans. Electromagn. Compat.*, vol. 43, no. 1, pp. 1–9, Feb. 2001.

[3] T. L. Wu, M. C. Lin, C. W. Lin, W. S. Jou, T. T. Shih, and W. H. Cheng, "A high electromagnetic immunity plastic composite package for a 10 Gibt/s optical transceiver modules," *J. Lightw. Technol.*, vol. 24, no. 8, pp. 3195–3201, Aug. 2006.

[4] K. Tatsuno, K. Yoshida, T. Kato, T. Hirataka, T. Miura, K. Fukuda, T. Ishikawa, M. Shimaoka, and T. Ishii, "High-performance and low cost plastic optical modules for access network system applications," *J. Lightw. Technol.*, vol. 17, no. 7, pp. 1211–1216, Jul. 1999.

[5] M. Fukuda, F. Ichikawa, Y. Shuto, H. Sato, Y. Yamada, K. Kato, S. Tohno, H. Toba, T. Sugie, J. Yoshida, K. Suzuki, O. Suzuji, and S. Kondo, "Plastic module of laser diode and photodiode mounted on planar lightwave circuit for access network," *J. Lightw. Technol.*, vol. 17, no. 7, pp. 1585–1590, Jul. 1999.

[6] W. H. Cheng, W. C. Hung, C. H. Lee, G. L. Hwang, W. S. Jou, and T. L. Wu, "Low cost and low electromagnetic interference packaging of optical transceiver modules," *J. Lightw. Technol.*, vol. 22, no. 9, pp. 2177–2183, Sep. 2004.

[7] C. M. Chang, J. C. Chiu, W. S. Jou, T. L. Wu, and W. H. Cheng, "New package scheme of a 2.5 Gb/s plastic transceiver module employing multiwall nanotubes for low electromagnetic interference," *J. Sel. Topics Quant. Electron.*, vol. 12, no. 5, pp. 1025–1031, Sep./Oct. 2006.

[8] C. M. Chang, M. C. Lin, J. C. Chiu, W. S. Jou, and W. H. Cheng, "High-performance electromagnetic susceptibility of plastic transceiver modules using carbon nanotubes," *J. Sel. Topics Quant. Electron.*, vol. 12, no. 6, pp. 1091–1096, Nov./Dec. 2006.

[9] E. D. Minot, Y. Yaish, V. Sazonova, J. Y. Park, M. Brink, and P. L. McEuen, "Turning carbon nanotube band gaps with strain," *Phys. Rev. Lett.*, vol. 90, no. 15, pp. 154601–154604, Apr. 2003.

[10] K. B. K. Teo *et al.*, "Carbon nanotube technology for solid state and vacuum electronics," *Proc. Inst. Elect. Eng., Circuits Devices Syst.*, vol. 151, no. 5, pp. 443–451, Oct. 2004.

[11] J. Li, Q. Ye, A. Cassell, H. T. Ng, R. Stevens, J. Han, and M. Meyyappan, "Bottom-up approach for carbon nanotube interconnects," *Appl. Phys. Lett.*, vol. 82, no. 15, pp. 2491–2493, Apr. 2003.

[12] J. A. Misewich, R. Martel, P. Avouris, J. C. Tsang, S. Heinze, and J. Tersoff, "Electrically induced optical emission from a carbon nanotube FET," *Science*, vol. 300, pp. 783–786, May 2003.

[13] M. F. Islam, E. Rojas, D. M. Bergey, A. T. Johnson, and A. G. Yodh, "High weight fraction surfactant solubilization of single-wall carbon nanotubes in water," *Nano Lett.*, vol. 3, pp. 269–273, 2003.

[14] V. C. Moore, M. S. Strano, E. H. Haroz, R. H. Hauge, R. E. Smalley, J. Schmidt, and Y. Talmon, "Individually suspended single-walled carbon nanotubes in various surfactants," *Nano Lett.*, vol. 3, pp. 1379–1382, 2003.

[15] O. Matarredona, H. Rhoads, Z. Li, J. H. Harwell, L. Balzano, and D. E. Resasco, "Dispersion of single-walled carbon nanotubes in aqueous solutions of the anionic surfactant NaDDBS," *J. Phys. Chem. B*, vol. 107, pp. 13357–13367, 2003.

[16] V. A. Sinani, M. K. Gheith, A. A. Yaroslavov, A. A. Rakhnyanskaya, K. Sun, A. A. Mamedov, J. P. Wicksted, and N. A. Kotov, "Aqueous dispersions of single-wall and multiwall carbon nanotubes with designed amphiphilic polycations," *J. Amer. Chem. Soc.*, vol. 127, pp. 3463–3472, 2005.

[17] Y. Kang and T. A. Taton, "Micelle-encapsulated carbon nanotubes: A route to nanotube composites," *J. Amer. Chem. Soc.*, vol. 125, pp. 5650–5651, 2003.

[18] C. Y. Li, L. Li, W. Cai, S. L. Kodjie, and K. K. Tenneti, "Nano-hybrid Shish-kebab: Polymer decorated carbon nanotubes," *Adv. Mater.*, vol. 17, pp. 1198–1202, 2005.

[19] W. S. Jou, H. Z. Cheng, and C. F. Hsu, "A carbon nanotube polymer-based composite with high electromagnetic shielding," *IEEE/TMS J. Electron. Mater.*, vol. 35, no. 3, pp. 462–470, Mar. 2006.

[20] S.-T. Lin, K.-L. Wei, T.-M. Lee, K.-C. Chiou, and J.-J. Lin, "Functionalizing multi-walled carbon nanotubes with poly(oxyalkylene)-amidoamines," *Nanotechnology*, vol. 17, pp. 3197–3203, 2006.

[21] T. Fukushima, A. Kosaka, Y. Ishimura, T. Yamamoto, T. Takigawa, N. Ishii, and T. Aida1, "Molecular ordering of organic molten salts triggered by single-walled carbon nanotubes," *Science*, vol. 300, pp. 2072–2074, June 27, 2003.

[22] B. K. Price, J. L. Hudson, and J. M. Tour, "Green chemical functionalization of single-walled carbon nanotubes in ionic liquids," *J. Amer. Chem. Soc.*, vol. 127, pp. 14867–14870, 2005.

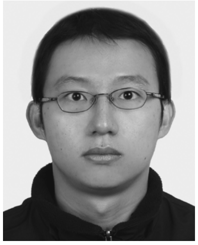
[23] H. M. Kim, K. Kim, S. J. Lee, J. Joo, H. S. Yoon, S. J. Cho, S. C. Lyu, and C. J. Lee, "Charge transport properties of composites of multiwalled carbon nanotube with metal catalyst and polymer: Application to electromagnetic interference shielding," *Curr. Appl. Phys.*, vol. 4, pp. 577–580, 2004.

[24] H. M. Kim, K. Kim, C. Y. Lee, J. Jooa, S. J. Cho, H. S. Yoon, D. A. Pejaković, J. W. Yoo, and A. J. Epstein, "Electrical conductivity and electromagnetic interference shielding of multiwalled carbon nanotube composites containing Fe catalyst," *Appl. Phys. Lett.*, vol. 84, no. 4, p. 26, Jan. 2004.

[25] *Standard Testing Method for Measuring the Electromagnet Electromagnetic Shielding Effectiveness of Planner Materials*, ASTM D4935-92, ASTM, Philadelphia, PA.

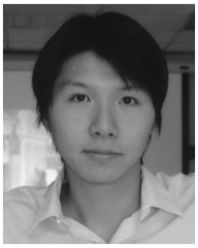
Chia-Ming Chang received the B.S. degree in electrical engineering from Tatung University, Taipei, Taiwan, R.O.C., in 1991, and the M.S. degree in electrooptical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, in 2002, where he is currently pursuing the Ph.D. degree. His Ph.D. dissertation research is in the area of optoelectronic packaging for telecommunication applications.

He is a Test Engineer at NXP Semiconductor Kaohsiung, Kaohsiung, Taiwan.

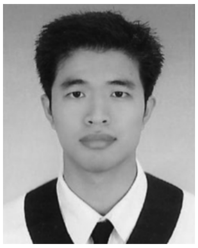


Jin-Chen Chiu received the B.S. degree in electrical engineering from National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C., in 2004, where he is currently pursuing the Ph.D. degree.

His research interests are mainly in the area of optoelectronic packaging for telecommunication applications.



Yi-Fen Lan received the B.S. degree from Feng Chia University, Taiwan, R.O.C., in 2004, and the M.S. degree from the National Chung Hsing University, Taiwan, both in chemical engineering. He is currently pursuing the Ph.D. degree at the National Taiwan University, Taipei, where his dissertation research is in the area of carbon material dispersion and applications for nanocomposites.



Jhe-Wei Lin received the B.S. degree from the National Central University, Jhong li, Taiwan, R.O.C., in 2006. He is currently pursuing the M.S. degree in electrooptical engineering at the National Sun Yat-sen University, Kaohsiung, Taiwan.

His research interests are optoelectronic packaging for telecommunication applications.

Chao-Yung Yeh was born in Kaohsiung, Taiwan, R.O.C., on July 10, 1957. He received the Ph.D. degree in optical science from the University of New Mexico, Albuquerque, in 1994.

From 1994 to 1996, he was a Laser Engineer with Novatec Laser System, Inc., Carlsbad, CA. From 1997 to 1998, he was a member of technical staff with Lightwave Link, Inc., Burbank, CA. From 2000 to 2003, he was a Senior Photonics Engineer with General Photonics, Inc., Chino, CA. He is currently is a Project Manager with Metal Industries Research and Development Center (MIRDC), Kaohsiung, Taiwan. His research interests are in the fields of ultrafast laser technology and ultrabroad bandwidth optoelectronics device development.

Wern-Shiarng Jou was born in Taipei, Taiwan, R.O.C., on April 4, 1960. He received the Ph.D. degree in chemical engineering from the University of Maryland, College Park, in 1990.

From 1990 to 1992, he was a Research Associate at the Chemical Engineering Department, University of Maryland, and the Cornell Injection Molding Program (CIMP), Cornell University, Ithaca, NY. He is a Professor in the Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, Kaoshiung, Taiwan. He served as a Consultant for Suiyo Industry Co., Taiwan. His research and development activities have been focused on the design and fabrication of new plastic composites, characterization of plastics, polymer processing, injection mold, and injection-molded products. His current research interests are electromagnetic shielding materials and nanocomposites.

Dr. Jou is a Member of the Society of Plastic Engineering (SPE) and serves as a Secretary for the Association of Mold Technology Development, R.O.C.

Jiang-Jen Lin was born in Taiwan, R.O.C., and received the Ph.D. degree in chemistry from the Georgia Institute Technology, Atlanta, in 1977.

From 1977 to 1979, he was a postdoctoral at Cornell University, Ithaca, NY, and Princeton University, Princeton, NJ. From 1979 to 1995, he was a Research Staff with Texaco Chemical Co. and Shell Development Co. From 1995 to 2005, he was a Professor with the Department of Chemical Engineering, National Chung-Hsing University, Taiwan. Currently, he is a Professor at the Institute of Polymer Science and Engineering, Nation Taiwan University. His research interests include polymeric surfactants, amphiphilic copolymers, self-assembly, layered silicate clays, nanosilicate platelets (nsp), organically modified clays, nanoparticle and pigment dispersion, and antimicrobial mechanism, polymer/biomaterial interaction.

Wood-Hi Cheng (M'95–SM'00) was born in Changhua, Taiwan, R.O.C., on June 3, 1944. He received the Ph.D. degree in physics from Oklahoma State University, Stillwater, in 1978.

From 1978 to 1980, he was a Research Associate with Telecommunication Laboratories, Taiwan. From 1980 to 1984, he was a Research Engineer with General Optronics, Edison, NJ. From 1984 to 1991, he was a Principal Design Engineer with Rockwell International, Newbury Park, CA. From 1991 to 1994, he was an Optoelectronic Packaging Manager with Tacan Corporation, Carlsbad, CA. He was a Consultant for Chunghwa Telecom Laboratories, Opto-Electronics and System Laboratories, and Chung-Shan Institute of Science and Technology, all in Taiwan. Currently, he is a Professor with the Institute of Electro-Optical Engineering and Director of the Southern Taiwan Opto-Electronic Center of Excellence, National Sun Yat-sen University, Kaoshiung, Taiwan. His research and development activities have been focused on the design and fabrication of high-speed semiconductor lasers for lightwave communications, highly efficient light coupling from lasers into fibers, fiber couplers, characterization of III-V semiconductors materials, and optoelectronic packaging. His current research interests include the design, fabrication, and finite-element method analysis for laser module packaging, high-speed laser module packaging for digital lightwave systems, fabrication of high-density wavelength division multiplexing components, and novel materials for electromagnetic shielding.

Dr. Cheng is a member of the Optical Society of America (OSA) and the Photonics Society of Chinese Americans. He was a Chair for the IEEE Lasers and Electro-Optics Society, Taipei Chapter, from 1999 to 2000, and is currently a Chair for the OSA, Taipei Chapter.