

B.D. GARDEN

**PROCEEDINGS
of the
29th.
INTERNATIONAL
WIRE and CABLE
SYMPOSIUM**

NOVEMBER 18-20 1980



SPONSORED BY THE
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PROCEEDINGS OF 29TH INTERNATIONAL WIRE AND CABLE SYMPOSIUM

Sponsored by
US Army Communications Research and Development Command
(CORADCOM) Fort Monmouth, N.J.

Cherry Hill, New Jersey
November 18, 19 and 20, 1980

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29th INTERNATIONAL WIRE
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TECHNICAL SESSIONS

Tuesday, 18 November 1980

9:30 a.m. Session I	Tutorial - Outlook For Voluntary Standards In U.S.A.
2:00 p.m. Session II	Cable Design I
2:00 p.m. Session III	Material

Wednesday, 19 November 1980

9:00 a.m. Session IV	Cable Design II
9:00 a.m. Session V	Connectors
2:00 p.m. Session VI	Fiber Optics I
2:00 p.m. Session VII	Fire Considerations

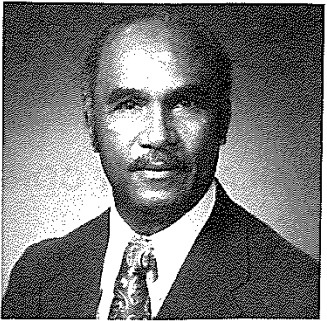
Thursday, 20 November 1980

9:00 a.m. Session VIII	Fiber Optics II
9:00 a.m. Session IX	Testing
2:00 p.m. Session X	Fiber Optics III
2:00 p.m. Session XI	Cable Applications

PAPERS

Responsibility for the contents rests upon the authors and not the symposium committee or its members. After the symposium, all the publication rights of each paper are reserved by their authors, and requests for republication of a paper should be addressed to the appropriate author. Abstracting is permitted, and it would be appreciated if the symposium is credited when abstracts or papers are republished. Requests for individual copies of papers should be addressed to the authors.

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MESSAGE FROM THE DIRECTOR

On behalf of CORADCOM and the symposium committee, welcome to the 29th Annual International Wire and Cable Symposium (IWCS). It is indeed gratifying to report that the symposium continues to attract world-wide attention from scientists, consultants, manufacturers, material suppliers and end product users of cables/wires. Many favorable comments were received on the technical contents and timely relevance of the papers presented during last year's symposium. Last year's attendance of 1583 included representatives from 404 U.S. companies, 30 foreign countries and 10 U.S. government agencies.

This year, the committee is also looking forward to a very exciting and enthusiastic meeting with many excellent papers scheduled for presentation. The technical program will begin with a tutorial session, entitled "Outlook For Voluntary Standards in U.S.A.", followed by ten individual sessions. The three sessions on fiber optics should be of special interest since twelve of the eighteen papers will contrast various developments and applications of fiber optics in seven foreign countries.

Committee members, Adolf Asam, ITT Electro Optical Products Division, Ken Bow, Dow Chemical U.S.A., Marta Farago, Northern Telecom Ltd., Irv Kolodny, General Cable Company, and Frank Short, Beldon Corporation, are retiring from the committee. Each member was extremely dedicated and contributed significantly to the success of the committee's objectives. On behalf of the committee, I wish to thank each one for their valuable contributions and wish them success in their future activities.

The committee recognizes the inconveniences encountered and concern expressed by many attendees with respect to the number of hotels/motels used for housing accommodations and their location or distance from the Hyatt. However, before another location can be selected, it must be approved by CORADCOM, the symposium sponsor. CORADCOM has stipulated that any location selected for the symposium must be within a reasonable distance of Fort Monmouth, preferably less than 100 miles, which limits the number of facilities with adequate accommodations.

The symposium cannot prosper without the sustained participation and attendance of representatives of the various industrial organizations and government activities. Therefore, the committee solicits the continued support of all members of the wire and cable industry. Again, I wish to express my appreciation to each committee member for their support, dedicated effort and cooperation. A very special thanks to Ms. Conti for her sincere dedication to the symposium objectives, her support and cooperation.


ELMER F. GODWIN

Director, IWCS

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AWARDS

Outstanding Technical Paper

- H. Lubars and J.A. Olszewski, General Cable Corp.—"Analysis of Structural Return Loss in CATV Coaxial Cable" 1968
- J.P. McCann, R. Sabia and B. Wargotz, Bell Laboratories—"Characterization of Filler and Insulation in Waterproof Cable" 1969
- D.E. Setzer and A.S. Windeler, Bell Laboratories—"A Low Capacitance Cable for the T2 Digital Transmission Line" 1970
- R. Lyenger, R. McClean and T. McManus, Bell Northern Research—"An Advanced Multi-Unit Coaxial Cable for Toll PCM Systems" 1971
- J.B. Howard, Bell Laboratories—"Stabilization Problems with Low Density Polyethylene Insulations" 1972
- Dr. H. Martin, Kabelmetal—"High Power Radio Frequency Coaxial Cables, Their Design and Rating" 1973
- D. Doty, AMP Inc.—"Mass Wire Insulation Displacing Termination of Flat Cable" 1974
- T.S. Choo, Dow Chemical U.S.A.—"Corrosion Studies on Shielding Materials for Underground Telephone Cables" 1975
- N.J. Cogelia, Bell Telephone Laboratories and G.K. Lavoie and J.F. Glahn, US Department of Interior—"Rodent Biting Pressure and Chemical Action and Their Effects on Wire and Cable Sheath" 1976
- Thomas K. McManus, Northern Telecom Canada Ltd. and R. Beveridge, Saskatchewan Telecommunications, Canada—"A New Generation of Filled Core Cable" 1977
- Fumio Suzuki, Shizuyoshi Sato, Akinori Mori and Yoichi Suzuki, Sumitomo Electric Industries, Ltd., Japan—"Microcoaxial Cables Insulated with Highly Expanded Polyethylene By Chemical Blowing Method" 1978
- S. Masaki, Y. Yamazaki and T. Ideguchi, Nippon Telegraph and Telephone Public Corporation, Japan—"New Aluminum Sheath Cable Used For Electromagnetic Shielding" 1979

Best Presentation

- N. Dean, B.I.C.C.—"The Development of Fully Filled Cables for the Distribution Network" 1968
- J.D. Kirk, Alberta Government Telephones—"Progress and Pitfalls of Rural Buried Cable" 1969
- Dr. O. Leuchs, Kable and Metalwerke—"A New Self-Extinguishing Hydrogen Chloride Binding PVC Jacketing Compound for Cables" 1970
- S. Nordblad, Telefonaktiebolaget L.M. Ericsson—"Multi-Paired Cable of Nonlayer Design for Low Capacitance Unbalance Telecommunication Network" 1971
- N. Kojima, Nippon Telegraph and Telephone—"New Type Paired Cable for High Speed PCM Transmission" 1972
- S. Kaufman, Bell Laboratories—"Reclamation of Water-Logged Buried PIC Telephone Cable" 1973
- R.J. Oakley, Northern Electric Co., Ltd.—"A Study into Paired Cable Crosstalk" 1974
- G.H. Webster, Bell Laboratories—"Material Savings by Design in Exchange and Trunk Telephone Cable" 1975
- J.E. Wimsey, United States Air Force—"The Bare Base Electrical Systems" 1976
- Michael DeLucia, Naval Ship Research and Development Center—"Highly Fire-Retardant Navy Shipboard Cable" 1977
- William L. Schmacher, AMP Inc.—"Design Considerations for Single Fiber Connector" 1978
- Richard C. Mondello, Bell Labs.—"Design and Manufacture of An Experimental Lightguide Cable For Undersea Transmission Systems" 1979
- I. Wadehra, IBM Corporation—"Performance of Polyvinyl Chloride Communication Cables in Modified Steiner Tunnel Test" 1979

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D. Abelson, Office of the STR,
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H. Collins, Washington Represent-
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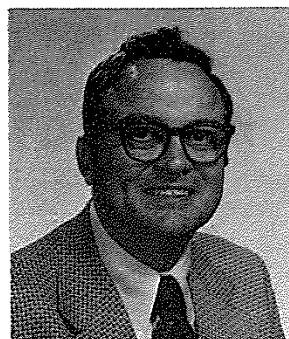
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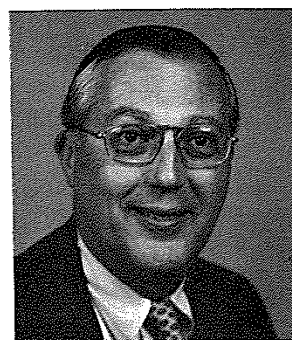
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APPLICATION OF SPACER FORMING TECHNIQUE TO COMMUNICATION CABLES

by

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Abstract

A new spacer forming technique has been developed. Flat plastic or laminated tapes are formed into V-shaped or U-shaped spacers and then stranded with each other in the stranding process. These spacers can accommodate optical fibers or star quads of insulated copper conductors, or can be used as the insulator of a coaxial core.

The technique was developed for optical cable in order that the spacers might preserve transmission characteristics and protect the optical fibers. It was then studied how to apply this technique to fabrication of coaxial cores and screened pair-type units. In coaxial cores, six V-shaped polyester spacers were used as the insulators between the inner conductor and outer conductor. A screened pair-type unit was formed by stranding five V-shaped spacers of polyester-laminated aluminum tape, and each spacer accommodated a star quad.

All of these cables which adopted the new spacer forming technique had sufficient transmission and mechanical properties, and a considerable number of spacer-type optical cables, in particular, have been put into actual use.

1. Introduction

A structure with spacers is supposed to be useful for avoiding microbending and preserving transmission characteristics of optical cables. In many reported cases, optical fibers are embedded in a groove spacer preformed by extrusion before fiber stranding.⁽¹⁾ The fabrication of these cables which use grooved spacers has generally two difficulties: preparation of the spacer, and synchronization between the spacer and fibers.

On the other hand, the spacer described here is constructed simultaneously with the fiber stranding process. Hence, a preformed spacer and special synchronization are not needed, and these advantages make it possible to use a conventional

stranding machine. Moreover, this technique has another advantage in that arbitrary stranding pitches can be easily designed as far as the stranding machine permits.

This paper describes the principle of spacer forming, the fabrication of optical cables, and their characteristics. Applications of this technique to coaxial and screened pair-type cables are also described.

2. Manufacturing Method (2)

The manufacturing method is shown in Fig. 1. In the stranding process, flat tapes are folded into the desired V-shaped or U-shape spacers by passing the tape through spacer formers located just before the assemblage die, and are then stranded with each other. A rather thick tape is considered to be preferable as the spacer from the point of view of tape forming and mechanical strength of the cable, and the spacer formers play an important role in this technique. The formers should precisely fold the flat tapes into the designated spacer configuration, which corresponds to the slit shape of the spacer formers. That is, V-shaped spacers can be obtained by passing the tape through a narrow rectangular slit, and U-shaped spacers, through a triangular slit. These mechanisms are shown in Fig. 2. The spacer forming tension should be as small as possible and should be almost equal for all of the spacers being stranded simultaneously. Maintaining uniformity in the tension and dimensions of spacers ensures a round, firm cable core. The use of a rotary assemblage die synchronized with the cage of the stranding machine is better than that of an ordinary stationary die, for precise settlement of spacers in the cable core can thus be assured.

After stranding of the spacers, the cable core is wrapped in some tapes. These wrapping

tapes also make the core rigid and tight in this technique. Each compartment defined by spacers can accommodate optical fibers, and also pairs or quads, and the spacers can be used as the insulator of the coaxial core.

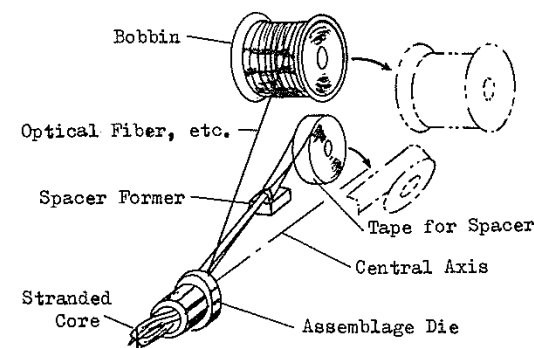


Fig. 1 Manufacturing Method

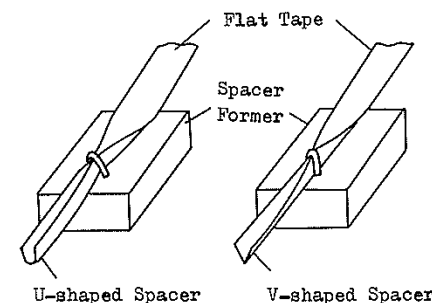


Fig. 2 Spacer Forming Mechanisms

3. Optical Cables with Spacers

3.1 Cable structure

The new spacer forming technique was first developed for optical cable. In general, lateral forces which arise due to microbending tend to increase the transmission loss of optical fibers. In order to avoid microbending, it is effective to accommodate the optical fibers in the cable in a loosely fitting manner. When the V-shaped or U-shaped spacers are large enough to accommodate optical fibers, the fibers are no longer susceptible to external forces in the cabling processes

and installation work.

After various investigations, it became clear that polyester tape with a thickness of 0.075mm to 0.2mm was adequate for the spacers of optical cable. Buckling load of the spacer is calculated by the following equation:

$$P = \frac{\pi^2 E t^3 B}{48 L^3}$$

where P : buckling load (kg)
t : thickness of spacer (mm)
E : Young's modulus of spacer (kg/mm²)
l : height of spacer (mm)
B : length of spacer (mm)

Polyester tape possesses a large Young's modulus, about 500 kg/mm², compared with other plastic tapes, which contributes to increase the buckling load given by the above equation. When two spacers are in contact with each other, as illustrated in Fig. 3, buckling load of 2kg, 8 times as large as that in the case of a single spacer, is derived from the equation. The value is sufficient for the cable core to withstand any lateral force caused throughout the cable manufacturing processes.

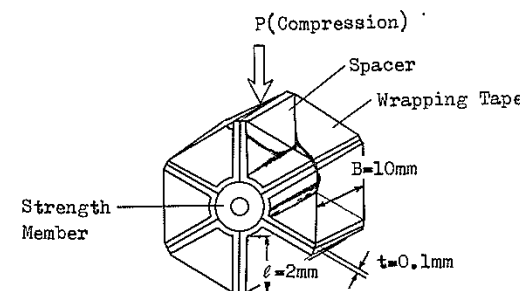


Fig. 3 Compression on Spacer

The typical structures of optical cables with spacers are shown in Fig. 4. The individual fiber can be easily identified by coloring the spacers rather than by employing colored fibers. The spacers accommodating individual fibers are stranded together around the central strength member. By adopting a larger size spacer, several fibers can be accommodated in one spacer. Use of the spacers easily leads to combining optical fibers with copper conductor pairs or quads, which are often included in optical cable, without additional loss increase.⁽⁴⁾ Figure 5 shows the structures of various spacer-type optical

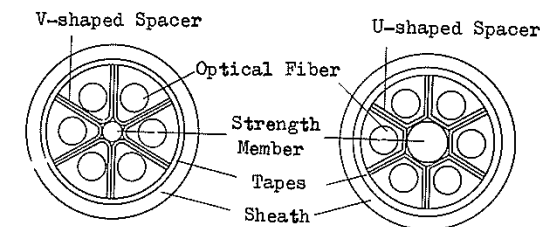


Fig. 4 Typical Structures of Spacer-Type Optical Fiber Cables

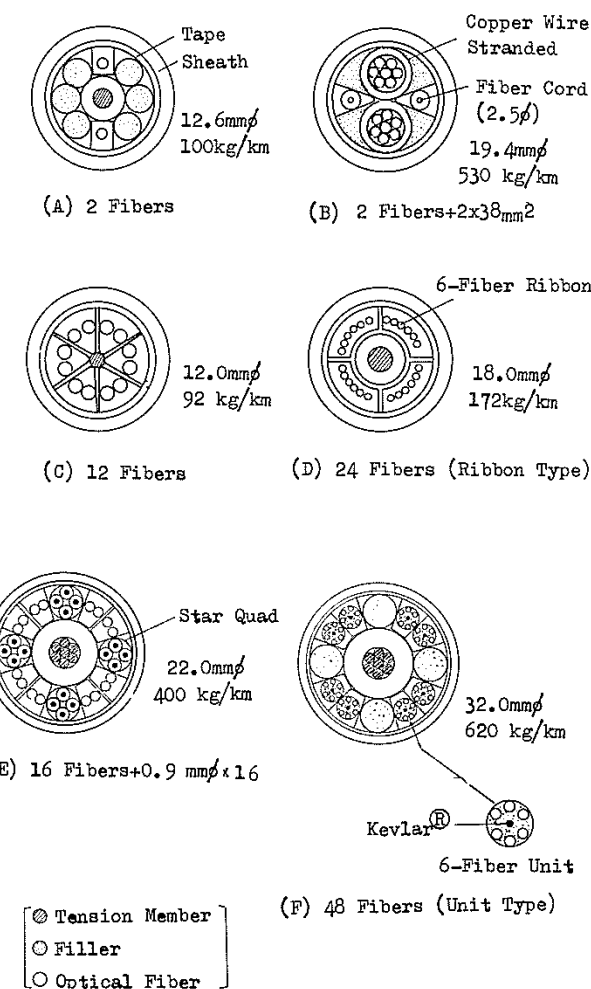


Fig. 5 Various Examples of Spacer-Type Optical Cables

cables. These cables have been put into actual use for optical communication lines at home and abroad.⁽⁵⁾⁽⁶⁾

3.2 General properties of spacer type optical cable

3.2.1 Transmission properties

In the cabling processes of optical cables, it is most important to conserve the inherent transmission characteristics of the optical fiber. The spacers contribute to making the optical fibers free from microbending. Figure 6 shows the average transmission loss change throughout the cabling processes for the fibers in cables (C) and (F) in Fig. 5, and almost the same results were confirmed for the other optical cables with spacers in Fig. 5. The fibers used had a core diameter of 50 μm and a cladding diameter of 125 μm with silica-type graded index profile, and were doubly coated with silicone and nylon.⁽³⁾ The stability of transmission characteristics is primarily caused by the spacers, which isolate the optical fibers from all external forces.

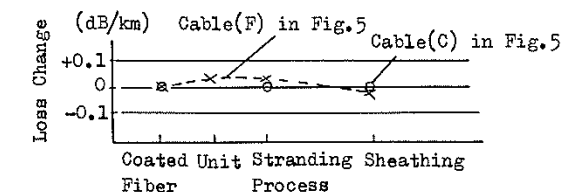


Fig. 6 Loss Change of Fibers in Cabling Processes

3.2.2 Mechanical properties

Table 1 shows the mechanical test conditions for cables (A), (C), and (F) in Fig. 5; no loss change and no fiber break were observed. The deformation of spacer-type optical cables under mechanical forces is generally less than that of non-spacer type optical cables.⁽⁷⁾ This effect is the result of the reactional forces yielded by the spacers and of the round, tight structure produced by using spacers to sturdily combine cable elements such as the strength member, wrapping tapes, etc. The results indicate that conventional installation techniques can be satisfactorily used for these optical cables with spacers.

Table 1 Mechanical Test Conditions

Item Cable	Tension	Bending	Compression	Impact
(A)	150 kg	R=200mm (R:Bending Radius 10 times	100kg 50mm Width	Weight 0.45kg x Hight 1.0m
(C)	150 kg	R=70mm 10 times	100kg 50mm Width	Weight 0.45kg x Hight 1.0m
(F)	1400 kg	R=100mm 10 times	500kg 50mm Width	Weight 2.3kg x Hight 0.9m

3.2.3 Temperature property

The transmission loss of the optical fiber in the spacer also shows stability even when temperature changes. Figure 7 shows the results of transmission loss change versus temperature for cable (C) in Fig. 5. The transmission loss change is less than 0.05dB/km ranging from -40°C to 60°C. This stability depends on the central strength member and the polyester spacer, both of which have coefficients of linear expansion smaller than that of coated fiber.

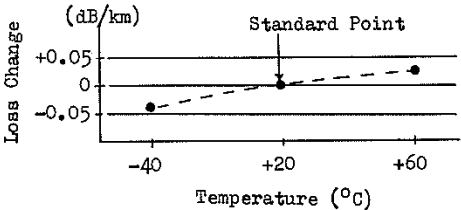


Fig. 7 Loss Change vs. Temperature for Cable (C) in Fig. 5

(kg/cm²)²/g/min.m

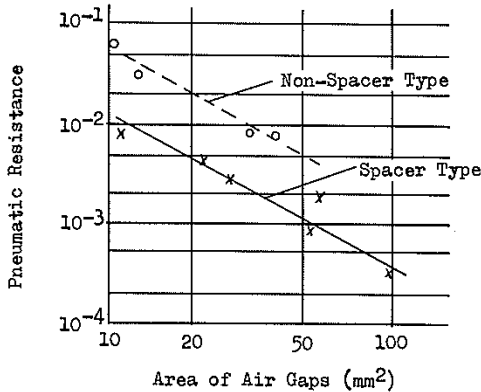


Fig. 8 Pneumatic Resistance vs. Area of Air Gaps

3.2.4 Penumatic property

It has been confirmed that the spacers, by increasing the air gaps in the cable, contribute to decreasing pneumatic resistance. Figure 8 shows the pneumatic resistances measured for fabricated spacer and non-spacer type optical cables.⁽⁸⁾ It can be clearly seen that the pneumatic resistance of spacer type optical cable is less than that of non-spacer type even in the case of equal cross-sectional area of gaps in the cable, since the air gaps in individual elements in the spacer type is larger than that in the non-spacer type.

3.2.5 Optical fiber unit with spacers

The fiber units with spacers shown in Fig. 9 were designed and manufactured. They can be easily used for optical cables with a relatively large number of fibers. Their unit structures are summarized in Table 2. The average transmission loss change between fiber coating and unit making was 0.05dB/km and 0.0dB/km for unit (A) and unit (B), respectively.

A compression test using unit (A) was carried out as illustrated in Fig. 10. After the unit was crushed, the optical fiber was pulled out. The tension necessary to remove the fiber was measured by a spring balance; the

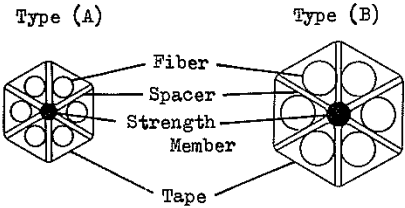


Fig. 9 6-Fiber Units with V-Spacers

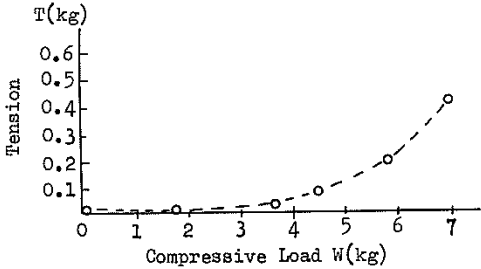


Fig. 11 Results of Compression Test

Table 2 Construction of Units

Unit Item	(A)	(B)
Fiber	Core : 50 m ϕ Cladding : 125 m ϕ Buffer : 350 m ϕ Silica-Type Graded Index Profile	
Jacket of Fiber	Nylon 0.7 mm ϕ	Nylon 0.9 mm ϕ
Strength Member	0.4 mm ϕ steel wire	1.0 mm ϕ steel wire
Spacer	Polyester 0.075mm(T) x 3.5mm(W)	Polyester 0.1mm(T) x 3.5mm(W)
Unit Diameter	3.7 mm ϕ	4.1 mm ϕ

results are shown in Fig. 11. It can be clearly seen that the fiber is not subjected to any compressive stress below a load of 3kg/110mm width. There is no compressive stress left on the fiber even if wrapping tapes are strongly wound. After the unit with spacers is fabricated, it is possible to use the conventional cabling techniques for the unit without any particular need for concern.

Another fiber-pulling test was done for unit (B). The relation between the maximum pulling tension of fiber removal and the length of the sample unit was investigated without lateral compressive load on the unit. From the results in Fig. 12, it can be seen that the fiber can be pulled out when the length of the unit is less than about 10m. Beyond 10m length, the fiber cannot be pulled out without damaging it. It was concluded that the fibers in the unit with spacers are sectionally free and are irremovable when they have longer lengths.

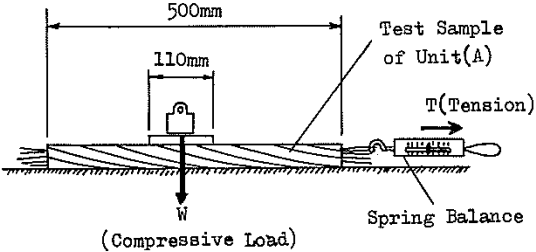


Fig. 10 Compression Test on Unit (A)

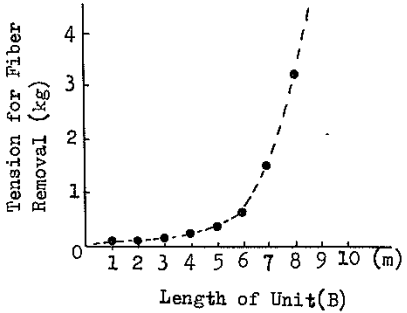


Fig. 12 Results of Fiber Pulling Test

4. Coaxial Core with Spacers

Application of the spacer forming technique to coaxial cores was investigated. Polyester spacers were included as the insulator between the inner conductor and outer conductor. The large amount of air included with the spacers was considered to decrease the equivalent dielectric constant of the insulation. Two coaxial cores with different sizes, as shown in Fig. 13 and Table 3, were designed and fabricated. The coaxial cores were fabricated at the same time by stranding six V-shaped polyester spacers around an inner conductor, forming an outer conductor of copper tape, and wrapping in laminated tape. Polyester tape was wound under the outer conductor to make the core tight. By the selection of the spacer stranding pitch, the electrical properties of the coaxial core can be finely controlled, because the lay length affects the volume of polyester contained as the insulator.

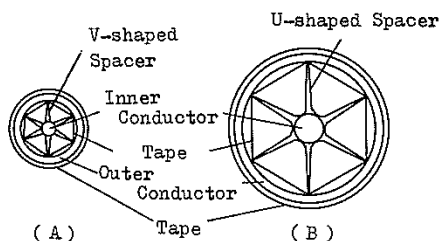


Fig. 13 Structures of Spacer Type Coaxial Cores

Table 3 Construction of Coaxial Cores

Item	Type	(A)	(B)
Inner Conductor		1.1 mm ϕ Copper Clad Steel	2.06 mm ϕ Copper
Spacer (Insulator)		Polyester Tape 0.125mm(T) x 3.5mm(W)	0.15mm(T) x 8mm(W)
Wrapping Tape of Spacer		0.025mm Thickness Polyester	0.025mm Thickness Polyester
Outer Conductor		Copper Tape 0.15mm(T) x 16mm(W)	Copper Tape 0.085mm(T) x 30mm(W)
Wrapping Tape of Core		Polyester (T:0.025mm) Laminated Aluminum (T:0.02mm)	Polyester (T:0.025mm) Laminated Aluminum (T:0.02mm)
Outer Diameter		5.0 mm ϕ	10 mm ϕ

Electrical properties of the coaxial cores are given in Table 4. The measured values of capacitance and characteristic impedance were reasonable in view of the values of the equivalent dielectric constant derived from the construction. Attenuation constant versus frequency was measured for both coaxial cores in the range from 10 to 100MHz, as shown in Fig. 14. The structural return loss (SRL) of both coaxial cores was less than 26dB in the frequency region from 10 to 300MHz. Figure 15 shows SRL characteristics of coaxial core (A). This figure indicates good uniformity in the manufacturing process.

Various sizes of coaxial cores with spacers can be easily produced by changing spacer sizes. Moreover, it is possible to insert as many optical fibers as desired into the coaxial core with spacers.

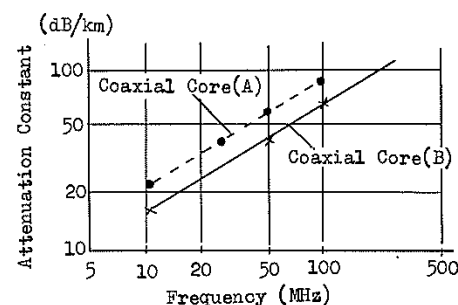


Fig. 14 Attenuation Constant vs. Frequency

Table 4 Electrical Properties of Coaxial Cores

Item	Type	(A)	(B)
Insulation Resistance		825 kM Ω ·km	1400 kM Ω ·km
Dielectric Strength		Insulation capable of withstanding for 1 minute DC test potential of 2000 V	
Conductor Resistance	Inner	56.29 Ω /km	5.06 Ω /km
	Outer	7.42 Ω /km	6.18 Ω /km
Capacitance		57.68 nF/km	51.11 nF/km
Characteristic Impedance		70.8 Ω	75.5 Ω
Attenuation Constant (at 10 MHz)		22.4 dB/km	16.2 dB/km

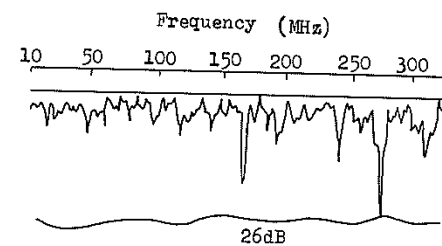


Fig. 15 Structural Return Loss of Core (A)

To clarify the improvement in crosstalk characteristics, far end crosstalk of screened units was measured in the frequency range from 100 KHz to 5 MHz together with that of non-screened units having no spacers. The results are shown in Fig. 17. The improvement of crosstalk characteristics was simply accomplished by using the spacer forming technique without any increase in the cabling process. When designed like unit (B), the unit diameter is almost equal to that of non-screened units.

5. Screened Pair-type Unit with Spacers

V-shaped or U-shaped spacers with metal can also be used as a screen of electromagnetic field. Polyester-laminated aluminum tape is suitable for this purpose. The structures of screened units with spacers are shown in Fig. 16 and Table 4. Five star quads and spacers were assembled with each other in an assemblage die, and then were wrapped in laminated tapes by a stranding machine without injuring the quads. Thus the quads were almost screened mutually regarding electromagnetic interferences.

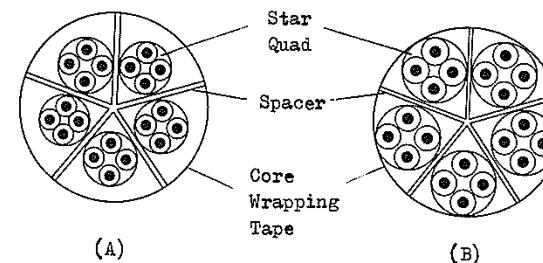


Fig. 16 Structures of Screened Units with Spacers

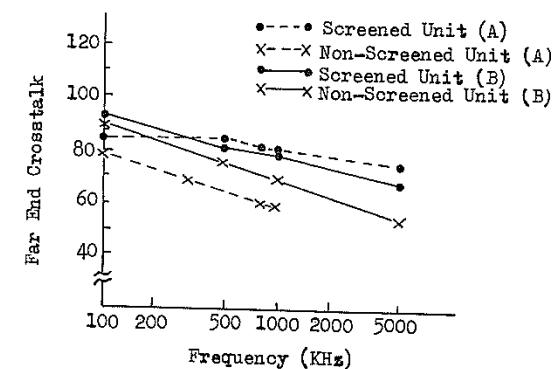


Fig. 17 Frequency Property of Far End Crosstalk within Unit

6. Complete Spacer-type Composite Cable

Optical fiber units of type (A) in Fig. 9, coaxial cores of type (A) in Fig. 13, and screened units of type (A) in Fig. 16 were assembled together by a conventional large-size stranding machine, and then were commonly sheathed as a complete spacer-type composite cable. Figure 18 shows the cross-sectional structure of the cable. Transmission loss of the fibers was almost un-

Table 5 Construction of Screened Units

Type Item	(A)	(B)
Conductor Diameter	0.5mm	0.65mm
Insulation Diameter	0.74mm	1.20mm
Blowing Degree	20%	30%
Spacer	Polyester (T: 0.1 mm) Laminated Aluminum Tape (T:0.025mm)	Polyester (T: 0.1 mm) Laminated Aluminum Tape (T:0.025 mm)
Core Wrapping Tape	Polyester (T:0.025mm) Laminated Aluminum Tape (T: 0.02mm)	Polyester (T:0.025mm) Laminated Aluminum Tape (T: 0.02mm)
Unit Diameter	9mm	9mm

changed throughout the cabling processes, as shown in Fig. 19, and electrical characteristics of coaxial cores and screened units were also stable. From this, the mechanical properties of each core were considered to be strong enough to withstand the considerable mechanical loads imposed on each core by the stranding and taking up operations. A general view of the composite cable is shown in Fig. 20.

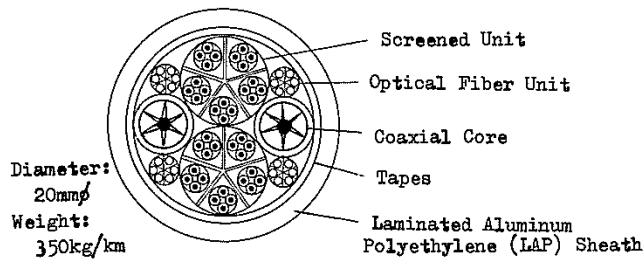


Fig. 18 Structure of Composite Cable

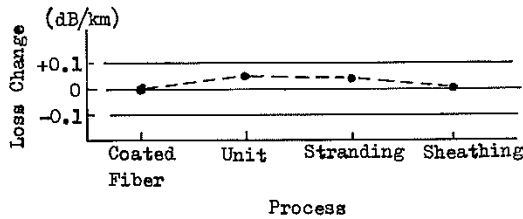


Fig. 19 Loss Change of Fibers in the Cabling Processes

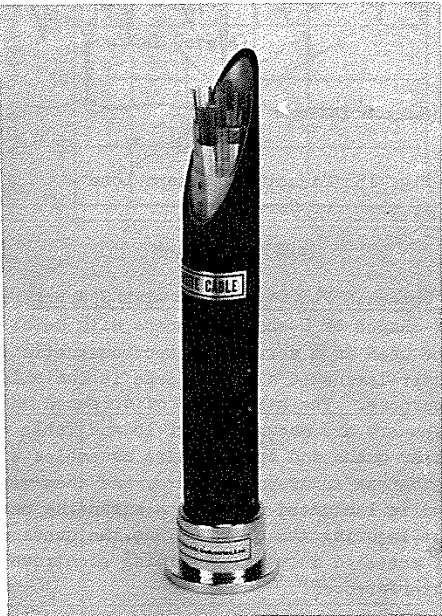


Fig. 20 General View of Composite Cable

7. Conclusion

Various kinds of optical cables utilizing the spacer forming technique were manufactured. These optical cables with spacers have excellent transmission and mechanical properties and have put into actual use at home and abroad.

By using this forming technique, it was seen that coaxial cables and screened pair-type cables could be easily manufactured and had outstanding electrical properties.

This technology will be further developed in the future to increase the range of applications.

Acknowledgements

The authors wish to thank Dr. N. Uchida of Ibaraki Electrical Communication Laboratory of N.T.T. and M. Hoshikawa and Y. Kameo of Sumitomo Electric Industries, Ltd. for their helpful comments and suggestions.

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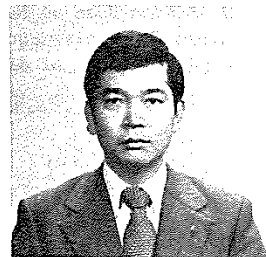
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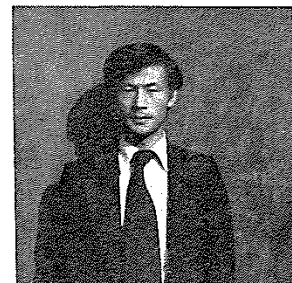
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MEAN POWER SUM FAR-END CROSSTALK OF PIC CABLES AS A FUNCTION OF AVERAGE TWIST HELIX ANGLE

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ABSTRACT

The mean power sum far-end crosstalk (FEXT) of the various designs of plastic insulated conductor (PIC) cables used in the Bell System (air core and waterproof, solid and expanded insulations, 19 through 26-gauge, 83 nF/mile and low capacitance) is a function of their average twist helix angle. Cables with small helix angles have stronger crosstalk coupling than cables with large helix angles. Consequently, 26-gauge solid insulation air core cable which has the smallest helix angle of any standard PIC cable also has the strongest (worst) mean FEXT coupling. At the other extreme, 19-gauge solid insulation waterproof cable which has the largest helix angle also has the weakest (best) mean FEXT coupling. The crosstalk spread between these two designs is as much as 6 dB.

Frequency scaling of mean FEXT is also a function of twist helix angle. The dependence, however, is slight—ranging from 5.7 dB per octave of frequency for 26-gauge air core to 6.2 dB per octave for 19-gauge solid insulation waterproof. This is from 0.3 dB less to 0.2 dB more than the classical 6 dB per octave rule.

Equations are presented which can be used to calculate the expected mean power sum FEXT performance of any copper PIC cable used in the Bell System. In addition, as long as pair twist schemes are judiciously chosen, these equations can also be used to predict the crosstalk performance of new cable designs.

1. INTRODUCTION

The maximum utilization of digital carrier systems on multipair cable depends to a large degree on the cable's crosstalk performance. Consequently, it has become increasingly desirable to know the crosstalk characteristics of the various cable designs. One way of obtaining this information is by actually measuring crosstalk on each cable design and, in fact, many such measurements have been made. However, knowledge of how crosstalk varies among these designs would allow predictions of not only the crosstalk performance of existing designs which have not been measured, but also of new designs which have yet to be manufactured.

A number of authors have examined the theoretical and practical aspects of modeling crosstalk in multipair cable.^{1,2} Such investigations are extremely useful for examining the effect of twist length selection, manufacturing tolerances, and other parameters on crosstalk. The present paper will not attempt to delve into similar analytical detail. Instead, simple empirical data on various Bell System cable designs will be examined and their crosstalk performance related to readily identifiable cable design parameters.

2. CROSSTALK MEASUREMENTS

Over the years a number of Bell System cables have been measured for crosstalk on a Computer Operated Transmission Measurement Set (COTMS).³ Normally, 50 consecutive pairs are connected to a pair fan-out and the 1225 pair-to-pair crosstalk combinations among those pairs measured at a number of frequencies.

The power sum crosstalk of a specific pair is then calculated by summing the pair-to-pair couplings into that pair on a power basis. Statistical parameters such as means and standard deviations can then be computed and reported for both the pair-to-pair and the power sum crosstalk distributions.

3. CROSSTALK TYPE EXAMINED

The highest bit rate digital carrier systems used on multipair cable (T2⁴ and T1C⁵) use power sum crosstalk rather than pair-to-pair crosstalk in the design of their repeatered lines. Consequently, power sum crosstalk data were examined. Power sum means were accumulated at five standard measurement frequencies—0.15, 0.772, 1.6, 3.15 and 6.3 MHz. Not all cables were measured at all five frequencies and so the number of measurements in the data base may change with frequency.

Depending on whether unidirectional or bidirectional carrier transmission is employed, either FEXT or NEXT (near end crosstalk) is important. This paper concentrates specifically on mean power sum FEXT.

As mentioned in Section 2, COTMS measurements are normally made on 50 pair groupings. All of the data presented here are therefore for 50 pair groups except for 25 pair cables. In these cases, the data are for all 25 pairs.

4. CABLE TYPES EXAMINED

Cable designs in the data base represent almost all standard 83 nF/mile copper PIC cables, i.e., air core and waterproof, solid and DEPIC (dual expanded plastic insulated conductor)⁶ insulations, and 19 through 26-gauge conductors. In addition to these standard cables, data were also examined on some "special" cables such as T2 LOCAP* cable (22-gauge DEPIC, 39 nF/mile for air core, and 46 nF/mile for waterproof)⁷, ICOT* cable (24-gauge DEPIC, 52 nF/mile for air core, and 60 nF/mile for waterproof)⁸, MAT* cable (25-gauge DEPIC, 64 nF/mile, air core)⁹, DUCTPIC* cable (26-gauge DEPIC, 83 nF/mile, air core)¹⁰ and an experimental 28-gauge cable (28-gauge solid insulation, 83 nF/mile, air core). These cables are termed "special" because they utilize shorter twist lengths and have a basically different twist spectrum than the standard cables. In addition, T2 LOCAP, ICOT and MAT cables have lower mutual capacitances than the standard 83 nF/mile.

5. CORRELATION OF MEAN FEXT WITH DIAMETER OVER DIELECTRIC

5.1 Standard Cables

Table 1 shows the number of FEXT measurements† and the average of the power sum FEXT means of each standard cable design at 0.15 MHz.

* Trademark of Western Electric.

† The term "measurements" will be used instead of "cables" because several measurements may have been made on different units in a single cable.