

1st European
Conference on
Optical Fibre
Communication



TN929.2-2
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1975

~~TN929.2-2~~ 7860319

TN929.11-53

062.2

1975

First European Conference on

OPTICAL FIBRE COMMUNICATION

16-18 September 1975



Organised by the

Electronics Division of the Institution of Electrical Engineers

in association with the

European Physical Society

Institute of Electrical and Electronics Engineers
(United Kingdom and Republic of Ireland Section)

Institute of Electrical Engineers of Japan

Institute of Physics

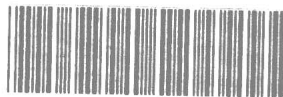
Institution of Electronic and Radio Engineers

Nachrichtentechnische Gesellschaft im VDE

Société des Electriciens, des Electroniciens et des Radioélectriciens

Venue

Institution of Electrical Engineers, Savoy Place, London WC2



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Published by the Institution of Electrical Engineers ISBN: 0 85296148 0

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Announcement

During the planning phase of the Conference it became clear that the interest in this subject was sufficient to demand a series of Conferences. Consideration was given to initiating an International or a European series.

After consultation with representatives from the European countries, the USA and Japan, it was recommended that this Conference should be the first of a series of European Conferences with the following Conference to be held in 1976 in France and a subsequent one in Germany in 1977.

Although the future Conferences will be organised on a European basis, it is the intention to strongly encourage participation on an international basis by invitation of the speakers and session chairmen, and by presentation of papers.

C. P. Sandbank
Chairman, IEE Optical and infra-red devices
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List of Authors

	<i>Page No.</i>		<i>Page No.</i>
Abe, A. ..	147	Geckeler, S. ..	51
Adams, M. J. ..	43	Gloge, D. ..	1
Akimoto, T. ..	57	Goodfellow, R. C. ..	119, 122
Albares, D. J. ..	168	Goodwin, A. R. ..	105
Arnaud, J. A. ..	5	Guttmann, J. ..	96
Ash, E. A. ..	131		
Auffret, R. ..	60	Harper, D. W. ..	62
		Hatta, T. ..	191
Baldwin, M. ..	209	Hayashi, I. ..	99
Beales, K. J. ..	27, 30, 33	Heinlein, W. E. ..	177
Belanov, A. S. ..	11	Hooper, R. C. ..	153
Berry, R. W. ..	153	Hoshikawa, M. ..	81
Black, P. W. ..	67	Hui Bon Hoa, D. ..	204
Blackmore, R. W. ..	182		
Boisrobert, C. Y. ..	60, 204	Ikeda, Y. ..	24
Bouillie, R. ..	194	Ikegami, T. ..	111
Budin, J. P. ..	117	Inada, K. ..	57
Burnham, R. D. ..	108	Inamura, Y. ..	144
		Inao, S. ..	70, 93
Callan, T. R. ..	84	Isomura, A. ..	54
Carroll, J. E. ..	135		
Conradi, J. ..	128	Jessop, A. ..	171
Cook, A. ..	67	Jocteur, R. ..	79
Cozannet, A. ..	60		
		Kaneko, H. ..	144
Dakin, J. P. ..	39	Kao, C. ..	8
Dalgleish, J. F. ..	87	Kent, A. H. ..	84, 185
Davies, D. E. N. ..	165	Khoe, G. D. ..	114
Day, C. R. ..	33	Kingsley, S. A. ..	165
Dianov, E. M. ..	11	Kobayashi, K. ..	138
DiMarcello, F. V. ..	36	Koizumi, K. ..	24
Duncan, W. J. ..	27, 30	Kojima, M. ..	57
Dunn, P. L. ..	30	Krumpholz, O. ..	96
		Kudo, T... ..	159
Evans, B. D. ..	48	Kunita, M. ..	188
Ezhov, G. I. ..	11	Kurokawa, K. ..	159
		Kurosaki, S. ..	81
Farrington, J. G. ..	135		
Fell, P. H. ..	182, 185	Lang, R... ..	138
Forber, A. ..	62	Lazay, P. D. ..	40
French, W. G. ..	40	Lee, J. D. ..	87
Fukuda, S. ..	191	Le Noane, G. ..	194
		Liertz, H. M. ..	76
Gallaup, J. L. ..	204	Lukas, H. H. ..	87
Gambling, W. A. ..	197		
Game, C. ..	171	Mabbitt, A. W. ..	119
		Maslowski, S. ..	64

List of Authors

	<i>Page No.</i>		<i>Page No.</i>
Matsuda, Y. ..	70, 93	Shiraishi, S. ..	81
Maurer, R. D. ..	46	Sigel, Jr., G. H. ...	48
McIntyre, R. J. ..	128	Simpson, J. R. ..	40
Mellor, J. R. ..	62	Sladen, F. M. E. ..	43
Midwinter, J. E. ..	16, 33	Slaughter, R. J. ...	84
Mikoshiha, K. ..	191	Snyder, A. W. ..	4
Miller, C. M. ..	90	Stern, J. R. ..	13
Milne, W. ..	122	Stewart, W. J. ..	19, 21
Minejima, Y. ..	188	Suzuki, S. ..	81
Minemura, K. ..	138		
Mizukami, T. ..	191	Takahashi, T. ..	93, 144
Mobsby, C. D. ..	119	Tanaka, G. ..	81
Müller, J. ..	125	Thompson, G. H. B. ..	203
Murata, H. ..	70, 93	Toge, T. ..	159
		Tréheux, M. ..	204
Nagai, Y. ..	159	Trimmel, H. R. ..	177
Nakahara, T. ..	81		
Nelson, B. P. ..	13	Ueno, Y. ..	147, 156
News, G. R. ..	27, 30, 33		
Norton, R. E. ..	108	Watts, J. K. ..	62
		Webb, P. P. ..	128
Oestreich, U. H. P. ..	73	Williams, D. ..	179
Ohgushi, Y. ..	147, 156	Williams, J. C. ..	36
Okura, K. ..	188	Wilson, M. G. F. ..	131
		Wonsiewicz, B. C. ..	40
Pan, J. J. ..	141		
Payne, D. N. ..	43, 197	Yamagata, J. ..	144, 188
Peters, J. R. ..	105	Yamamoto, Y. ..	54
Pfeiffer, E. ..	96	Yamanishi, T. ..	54
Pion, M. ..	105	Yasugi, T. ..	156
Pitt, C. W. ..	131		
Prokhorov, A. M. ..	11		
Rawson, E. G. ..	108		
Reeve, M. H. ..	16		
Roberts, F. F. ..	150		
Rousseau, M. ..	174		
Sanada, K. ..	57		
Sandbank, C. P. ..	162		
Schicketanz, D. ...	51, 102		
Schwartz, M. I. ..	201		
Scifres, D. R. ..	108		
Sekizawa, T. ..	159		
Senmoto, S. ..	144, 188		
Shimohori, Y. ..	191		

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<i>Page No.</i>	<i>168</i>	<i>D. J. Albares</i> Potential military optical fibre communications
	<i>5</i>	<i>J. A. Arnaud</i> Pulse broadening in multimode optical fibers
	<i>131</i>	<i>E. A. Ash, C. W. Pitt and M. G. F. Wilson</i> Integrated optics for fibre communications systems
	<i>60</i>	<i>R. Auffret, C. Y. Boisrobert and A. Cozannet</i> Wobulation technique applied to optical fibre transfer function measurement
	<i>209</i>	<i>M. Baldwin</i> Data transmission in naval ships by fibre optics
	<i>30</i>	<i>K. J. Beales, W. J. Duncan, P. L. Dunn and G. R. Newns</i> Preparation of dry glasses for optical fibres
	<i>27</i>	<i>K. J. Beales, W. J. Duncan and G. R. Newns</i> Sodium borosilicate glass for optical fibres
	<i>11</i>	<i>A. S. Belanov, E. M. Dianov, G. I. Ezhov and A. M. Prokhorov</i> Multilayer optical waveguides
	<i>153</i>	<i>R. W. Berry and R. C. Hooper</i> Practical design requirements for optical fibre transmission systems
	<i>67</i>	<i>P. W. Black and A. Cook</i> Properties of optical fibre in cabling
	<i>182</i>	<i>R. W. Blackmore and P. H. Fell</i> 8.448 Mbits optical fibre system
	<i>204</i>	<i>C. Y. Boisrobert, D. Hui Bon Hoa, M. Tréheux and J. L. Gallaup</i> Digital repeater design
	<i>117</i>	<i>J. P. Budin</i> Transversely pumped $\text{Nd}_x\text{La}_{1-x}\text{P}_5\text{O}_{14}$ laser performance
	<i>128</i>	<i>J. Conradi, P. P. Webb and R. J. McIntyre</i> Silicon reach-through avalanche photodiodes for fiber optic applications

Page No.	39	<i>J. P. Dakin</i> A new method for the cheap and simple production of low-loss silica-based optical waveguides
	87	<i>J. F. Dalgleish, H. H. Lukas and J. D. Lee</i> Splicing-of optical fibres
	165	<i>D. E. N. Davies and S. A. Kingsley</i> A novel optical fibre telemetry highway
	33	<i>C. R. Day, K. J. Beales, J. E. Midwinter and G. R. Newns</i> The development of optical fibre using sodium borosilicate glasses and the double crucible technique
	36	<i>F. V. DiMarcello and J. C. Williams</i> Reproducibility of optical fibers prepared by a chemical vapor deposition process
	135	<i>J. G. Farrington and J. E. Carroll</i> Sub nanosecond pulsing of GaAs stripe lasers
	185	<i>P. H. Fell and A. H. Kent</i> Television transmission equipment and systems
	197	<i>W. A. Gambling and D. N. Payne</i> Some experimental aspects of propagation in optical fibres
	171	<i>C. Game and A. Jessop</i> Random coding for digital optical systems
	51	<i>S. Geckeler and D. Schicketanz</i> The influence of mechanical stress on the transfer characteristics of optical fibres
	1	<i>D. Gloge</i> Principles of optical fiber transmission
	122	<i>R. C. Goodfellow and W. Milne</i> The dynamic impedance and high frequency performance of small area high radiance gallium arsenide L.E.D.s
	105	<i>A. R. Goodwin, J. R. Peters and M. Pion</i> Temperature-stable continuously operating $\text{Ga}_x\text{Al}_{1-x}\text{As}$ injection lasers

Contents

Page No.	96	<i>J. Guttmann, O. Krumpholz and E. Pfeiffer</i> Multi-pole optical fibre-fibre connector
	62	<i>D. W. Harper, A. Forber, J. R. Mellor and J. K. Watts</i> Medium loss optical fibres and some features of their use in practical systems
	99	<i>I. Hayashi</i> Status of (Ga,Al)As heterostructure laser research in Japan
	177	<i>W. E. Heinlein and H. R. Trimmel</i> Repeater spacings of 8 Mbit/s and 34 Mbit/s transmission systems using multimode optical waveguides and LEDs
	111	<i>T. Ikegami</i> Spectrum broadening and tailing effect in directly modulated injection lasers
	57	<i>K. Inada, T. Akimoto, M. Kojima and K. Sanada</i> Transmission characteristics of a low-loss silicone-clad fused silica-core fibre
	54	<i>A. Isomura, Y. Yamamoto and T. Yamanishi</i> Plastic coating of optical glass fiber
	79	<i>R. Jocteur</i> Cabling of low-loss optical fibers
	8	<i>C. Kao</i> Estimating the dispersion effects in a practical multimode waveguide cable for fiber systems
	114	<i>G. D. Khoe</i> Power coupling from junction lasers into single mode optical fibres
	138	<i>K. Kobayashi, R. Lang and K. Minemura</i> Novel methods for high speed modulation of semiconductor lasers
	24	<i>K. Koizumi and Y. Ikeda</i> Low-loss light-focusing fibers made by a continuous process

Contents

Page No.	159	<i>K. Kurokawa, T. Sekizawa, T. Kudo, T. Toge and Y. Nagai</i> A 400 Mb/s experimental transmission system using a graded index fiber
	40	<i>P. D. Lazay, J. R. Simpson, W. G. French and B. C. Wonsiewicz</i> Interference microscopy : automatic analysis of optical fiber refractive index profiles
	194	<i>G. Le Noane and R. Bouillie</i> Connections for optical cables : design and measurements
	76	<i>H. M. Liertz</i> Experimental determination of admissible mechanical loads of optical wave guides with respect to cabling process influences
	119	<i>A. W. Mabbitt, C. D. Mobsby and R. C. Goodfellow</i> High radiance gallium indium arsenide light emitting diodes for fibre optic communication applications
	64	<i>S. Maslowski</i> Development of cables and connectors for optical fibres
	46	<i>R. D. Maurer</i> Fibers for ten kilometer—one hundred megabit per second transmission
	90	<i>C. M. Miller</i> Loose tube splices for optical fibers
	191	<i>T. Mizukami, T. Hatta, S. Fukuda, K. Mikoshiba and Y. Shimohori</i> Spectral loss performances of optical fiber cables using plastic spacer and metal tube
	125	<i>J. Müller</i> Fast and sensitive thin film silicon pin-photodiodes
	70	<i>H. Murata, S. Inao and Y. Matsuda</i> Step index type optical fiber cable
	93	<i>H. Murata, S. Inao, Y. Matsuda and T. Takahashi</i> Splicing of optical fiber cable on site

Page No.	81	<i>T. Nakahara, M. Hoshikawa, S. Suzuki, S. Shiraishi, S. Kurosaki and G. Tanaka</i>	Design and performances of optical fiber cables
	13	<i>B. P. Nelson and J. R. Stern</i>	Pulse propagation measurements on slightly overmoded glass fibres
	73	<i>U. H. P. Oestreich</i>	The application of the Weibull-distribution to the mechanical reliability of optical fibers for cables
	188	<i>K. Okura, J. Yamagata, S. Senmoto, Y. Minejima and M. Kunita</i>	A video transmission system using fibre cable
	141	<i>J. J. Pan</i>	High-performance, wideband fiber optic repeater and its application
	43	<i>D. N. Payne, F. M. E. Sladen and M. J. Adams</i>	Index profile determination in graded index fibres
	108	<i>E. G. Rawson, R. E. Norton, R. D. Burnham and D. R. Scifres</i>	A striped-substrate, double-heterostructure source for optical communication
	16	<i>M. H. Reeve and J. E. Midwinter</i>	Studies of tunnelling from the guided modes of a multimode fibre
	150	<i>F. F. Roberts</i>	Optical fibres look into the real world
	174	<i>M. Rousseau</i>	Transmission code and receiver selection for optical fibres PCM communications
	162	<i>C. P. Sandbank</i>	The prospects for fibre optic communication systems
	102	<i>D. Schickel</i>	Large signal behaviour of DHS laserdiodes
	201	<i>M. I. Schwartz</i>	Optical fiber parameters and optical cable design considerations

Contents

Page No.	48	<i>G. H. Sigel, Jr. and B. D. Evans</i> Prospects for radiation resistant fiber optics
	84	<i>R. J. Slaughter, A. H. Kent and T. R. Callan</i> A duct installation of 2-fibre optical cable
	4	<i>A. W. Snyder</i> Ray analysis of pulse distortion due to scattering
	21	<i>W. J. Stewart</i> Fibre characterisation by use of the relation between the characteristics of leaky modes in optical fibres and the fibre parameters
	19	<i>W. J. Stewart</i> Mode conversion due to periodic distortions of the fibre axis
	203	<i>G. H. B. Thompson</i> Laterally confined injection lasers for optical communications
	147	<i>Y. Ueno, Y. Ohgushi and A. Abe</i> A 40 Mb/s and a 400 Mb/s repeater for fiber optic communication
	156	<i>Y. Ueno, Y. Ohgushi and T. Yasugi</i> An optical fiber cable communication system using pulse-interval modulation
	179	<i>D. Williams</i> The military applications of fibre optical communication
	144	<i>J. Yamagata, S. Senmoto, Y. Inamura, H. Kaneko and T. Takahashi</i> A 32 Mb/s regenerative repeater for fibre cable transmission

PRINCIPLES OF OPTICAL FIBER TRANSMISSION

D. Gloge*

To describe modern fibers, one must find a compromise between the inadequate simplicity of the dielectric slab analog and the complexity of the rigorous field solutions of the circular cylindrical rod [1]. Most useful is a concept which can be stripped of irrelevant information from the beginning, applies to the classical step-index as well as to graded-index profiles, and can be reduced to a few clear pictures and diagrams. By combining suitable pairs of the HE and the EH solutions of the cylindrical rod, for example, one gains a simple formalism of mode character which sidesteps bizarre beat phenomena that occur in fibers, but are of no concern when direct detection is used [2]. In a next step, one can decompose the fields so gained into locally plain wavelets. Lines drawn along the wave normals, represent "mode-equivalent" rays which follow spiralling paths bouncing off the core walls. Projected onto the fiber end, such paths typically describe re-iterative star patterns. These patterns and their distortion in distorted fibers yield meaningful insight into the mode behavior.

Of course, rays and wave vectors are derivable from the mode parameters directly without knowledge of the mode field. This is as true for the step profile as for any (gently) graded index profile. In fact, in case of the graded index, the local wave vector often serves as the starting point for field computations (Wentzel-Kramers-Brillouin method [3]). So far, these arguments have not taken us beyond classical ray optics. However, a formal extrapolation of the wave vector concept is valid in regions where one or more of its components appear imaginary (which foils the classical ray concept). The magnitude of the imaginary component determines the evanescent field decay in that direction [4]. A phenomenon explainable in these terms is the strong cladding field decay of many fiber modes at cutoff. (This behavior is in sharp contrast with the modes of the slab which are unbounded at cutoff.) Arguments based on the cladding wave vector also explain the selective leakage instrumental in suppressing modes other than the fundamental in near-single-mode operation (W-fiber [5]).

Single-mode operation avoids the signal impairment that results from group delay differences in multimode fibers, but apart from the requirements it imposes on the optical source, single-mode operation compounds the difficulties of fiber splicing and cabling. The latter task requires fibers that are insensitive to "microbending", a distortion of the fiber axis (imposed from the outside) that causes a signal loss both in single- and multimode operation as a result of a power transfer

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from propagating modes to undesired or lossy modes [6]. To control this effect, one must attempt to place the beat wavelength associated with the critical transfer into a range where the fiber is stiff enough to resist distortions. Unfortunately, optimum microbending control and the best splicing characteristics are usually incompatible objectives and require a compromise; single-mode operation, if desired, further narrows the options of this compromise.

If one chooses multimode operation, one has to cope with the spread of the modal group delays. One can compute the delays (in seconds per unit length) from the frequency derivative $d\beta/d\omega$ of the modal propagation constant β by way of a very general variational principle which links these quantities to a (weighted) average of the magnitude of the local wave vector $kn(x,y)$ in the waveguide cross section [7]. More specifically

$$\beta \frac{d\beta}{d\omega} = \int kn \frac{d(kn)}{d\omega} p(x,y) dx dy$$

where the integration is over the entire cross-sectional area. If one interpretes $p(x,y)$ as the probability of a ray to traverse the cross section at (x,y) , the equation above quickly reduces to the formula generally used to compute the time of flight along a geometrical ray path. In more general (and more accurate) terms, however, $p(x,y)$ is the modal power density normalized for unit power flow through the cross section.

The best signal performance results for an index profile $n(x,y)$ for which the integral on the right is (as closely as possible) proportional to β for all the modes of the guide so that $d\beta/d\omega$ is nearly invariant with mode number. Finding this profile is a difficult optimization problem affected also by the material-related interdependence between n and $dn/d\omega$ [8]. Some knowledge of this interdependence and an intelligent choice of trial functions are necessary. No reason exists, however, why the profile cannot be designed to such precision that the transmission of hundreds of Megabit per second is feasible over the full repeater spacing that modern low-loss fibers offer.

This summary is necessarily sketchy. I hope it will arouse an interest in a more detailed talk. It is my intention to emphasize successful concepts, perceptions, and techniques of analysis rather than to present a finished theory of fibers. On the other hand, I hope that exemplary demonstrations of such concepts and techniques at work will illuminate the more urgent problems of modern fiber technology and suggest ways of solving them.

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RAY ANALYSIS OF PULSE DISTORTION DUE TO SCATTERING

Allan W. Snyder *

Coupled power equations¹ have proven to be a valuable tool for the analysis of pulse distortion due to imperfections on optical waveguides. These equations were derived from coupled mode theory using statistical averaging methods. However, coupled mode theory is unnecessary when the waveguide is overmoded. Then, the simplest ray analysis applies, in which irregularities are characterized by their differential scattering cross section σ_d and cladding loss is included via Fresnel's classical laws for reflection, leading to²

$$\frac{\partial I}{\partial z} + \frac{1}{v} \frac{\partial I}{\partial t} + \alpha I = \int_0^\theta c S(\theta, \theta') I(\theta', z) \theta' d\theta' \quad (1)$$

$$\alpha = \alpha_a + N\sigma_{\text{tot}} \quad (2)$$

$$S(\theta, \theta') = N \int_0^{2\pi} \sigma_d(\theta, \theta', \phi) d\phi \quad (3)$$

$$v(\theta) = c \cos\theta \cong c(1 + \theta^2/2) \quad (4)$$

I is the energy distribution within a hollow annular cone bounded by angles θ and $\theta + d\theta$ where θ and ϕ are the spherical polar angles referred to the fibre axis, i.e. θ is the inclination of the ray to the fibre axis and ϕ the azimuthal angle. N is the number density of scatterers per unit volume and σ_{tot} is the total scattering cross section. θ_c is the complement of the critical angle.

Equation (1) reduces to a diffusion equation for highly forward directed scatterers. For Rayleigh scatterers, there is negligible distortion but significant attenuation due to scattering, i.e.

$$I(\theta, z, t) \cong e^{-\alpha z} I(\theta, 0, t - z/v) \quad (5)$$

We discuss the condition under which eq. (1) is equivalent to the coupled power formalism. Several types of scattering mechanisms are analysed for arbitrary illumination and the Greens function for Rayleigh scatterers is discussed.

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PULSE BROADENING IN MULTIMODE OPTICAL FIBERS

J A Arnaud *

The broadening of optical pulses propagating in multimode optical fibers can be evaluated by comparing the times of flight of pulses moving along rays excited by the source. To evaluate this time of flight, it is essential to know the radial variation of the ratio of the local phase to group velocity in the material.¹ We shall call this variation the "inhomogeneous dispersion" of the fiber.

We shall give first a closed form expression of the impulse response of a fiber when the square of the refractive index is a constant plus a power of the distance from axis. This profile was first discussed by Gloge and Marcattili.² However, inhomogeneous dispersion was neglected. The impulse width obtained from our expression (see below), which takes inhomogeneous dispersion into account, is in substantial agreement with that reported by Olshansky and Keck³ who, however, do not give the impulse response. Next, we give the impulse width for small but otherwise arbitrary departures of the square of the refractive index profile from a square-law.⁴ This more exact expression is needed when the deviation of the profile from square law goes beyond r^4 terms, or when the square of the refractive index is not a linear function of dopant concentration. Application to germania doped fibers will be done on the basis of recent refractive index measurements by Fleming⁵. Finally, we shall compare the pulse broadening obtained by solving numerically the scalar Helmholtz equation for stepped profiles to that obtained by ray (or WKB) methods.

A few algebraic results relevant to the above discussion are displayed below. Let us first assume that the square of the free wavenumber $k(r, \omega) \equiv (\omega/c) n(r, \omega)$ has the form

$$K(R, \Omega) = \begin{cases} K_0(\Omega) - K_k(\Omega) R^k, & R < A \\ K_0(\Omega) - K_k(\Omega) A^k, & R \geq A \end{cases} \quad (1)$$

where capital letters denote the squares of the corresponding small letters, namely $K \equiv k^2$, $R \equiv r^2$, $A \equiv a^2$, $\Omega \equiv \omega^2$ and a is the core radius (with the notation in Ref. 2 and 3, $2k \equiv \alpha$). Assuming that the source is lambertian, the impulse response is found to be exactly (within ray optics)

$$P(t) = (K_0 A/2) \beta [(1-\beta^2)/(1-\beta_s^2)]^{1/k} [D' - (1-D')\beta^{-2}] \quad (2a)$$

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