Viscoelastic properties of bamboo

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Dynamic viscoelastic properties of bamboo were determined in torsion and bending. Damping, measured by tan δ, in dry bamboo was relatively small, about 0.01 in bending and 0.02 to 0.03 in torsion, with little dependence on frequency in the audio range. In wet bamboo, damping was somewhat greater: 0.012–0.015 in bending and 0.03–0.04 in torsion. The anisotropy in damping implies a purely cellular model is insufficient; there is large-scale molecular orientation or at least two distinct solid phases.

1. Introduction

Materials of biological origin contain natural polymers, and they therefore can be expected to exhibit viscoelastic behaviour. For example, wood is a cellular composite of biological origin, based on lignin and cellulose which are natural macromolecules [1]. In addition to the results adduced in [2], numerous spectra (tan δ versus temperature at a constant frequency of 1 Hz or 1 kHz) have been obtained for dry woods, lignin, and delignified wood, as well as coal, amber and oil shale for comparison [3]. Woods, such as spruce and beech, exhibit β peaks corresponding to a loss tangent of 0.02–0.03 at a temperature of about 200 K, tan $\delta \approx 0.02$ at room temperature (about 300 K), and an α peak of tan $\delta \approx 0.08$ at about 400 K. Spectra for lignin, bituminous coal and amber had similar overall characteristics.

Bamboo has an interesting microstructure and macrostructure with hierarchical features which contribute to its structural integrity [4]. Specifically, bamboo contains fibre-like structural features known as bundle sheaths [4] as well as oriented porosity along the stem axis. Bamboo, moreover, has functional gradient properties in which there is a distribution of Young's modulus across the culm (stem) cross-section [5]. Plant fibrous materials, including jute, bamboo, sisal, and bamboo, contain lignin and cellulose [6], in which cellulose microfibrils are embedded in a matrix of lignin and hemicellulose. Bamboo contains 44.5% cellulose, 20.5% lignin, 32% soluble matter, 0.3% nitrogen and 2% ash [5], while by contrast, a wood such as Jack pine contains 45% cellulose, 28.6% lignin, 10.8% mannan, 1.4% araban, 7.1% xylan [7] (not all components are quoted here). Bamboo also exhibits significant anisotropy in strength: it is more than ten times stronger in tension in the longitudinal direction than in the transverse direction [6]. To the authors' knowledge, frequency-dependent viscoelastic studies of bamboo have not been conducted. The present work deals with viscoelasticity of bamboo in torsion and bending.

2. Experimental procedure

Bamboo stem segments of outer diameter 80–82 mm and wall thickness 9 mm were cut two months prior to testing from a region 16 m high in a stem which had grown for 2 years. The bamboo was Mousou bamboo (*Phyllostachys edulis Riv.*). A cross-sectional micrograph is shown in Fig. 1a and a cross-sectional fracture surface is shown in Fig. 1b. A section about 250 mm long was allowed to air-dry; it was rough-cut with a bandsaw and was shaped via an abrasive method to prismatic bars of rectangular cross-section, with the long dimension parallel to the stem axis of the bamboo. Following specimen shaping, specimens were supported at the ends to allow free flow of air to allow equilibration to the laboratory environment in which the temperature was $22 \pm 0.5\,^{\circ}$C and the relative humidity was $45 \pm 1\%$. Specimens were weighed daily. Weight was lost due to evaporation of moisture over a period of about 1 week, after which the weight remained stable. Final specimen dimensions and density were 3.02 mm × 3.02 mm × 52.1 mm, 0.86 g cm^{-3} for specimen 1, 3.05 mm × 3.05 mm × 52.2 mm, 1.08 g cm^{-3} for specimen 2. These specimens were examined for viscoelastic behaviour as described below. In view of similarities between bamboo and wood, which has a known dependence of properties upon hydration [8], some bamboo specimens after testing at room humidity, were immersed in water and again weighed periodically to evaluate the approach to equilibrium. This wet bamboo was also subjected to a study of viscoelastic properties. Specimen dimensions were

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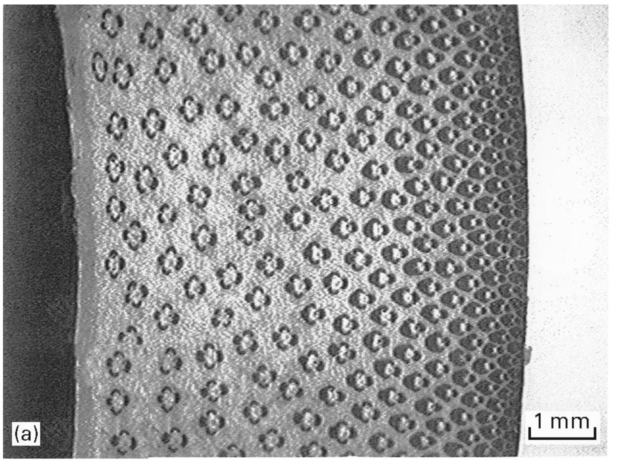

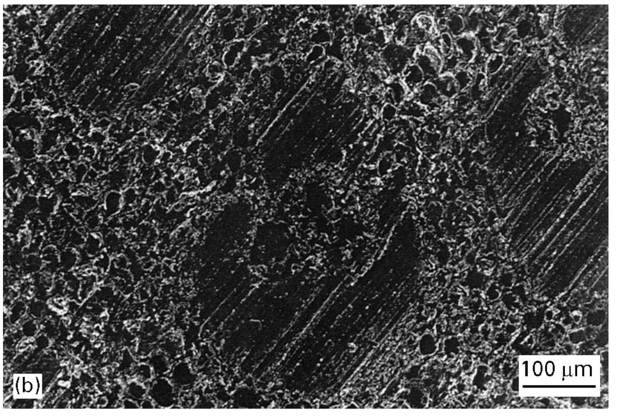

Figure 1 (a) Micrograph of the cross-section of bamboo. (b) Cross-sectional fracture surface of bamboo.

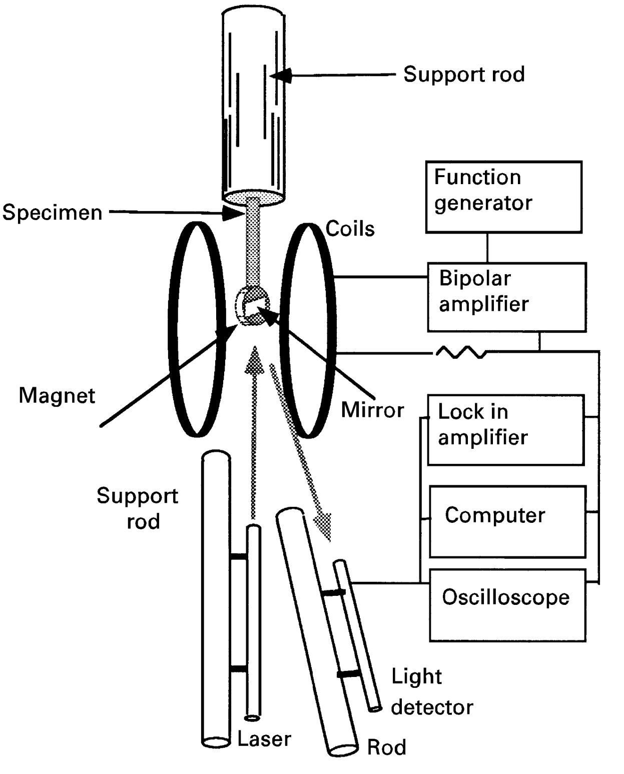

Figure 2 Diagram of the apparatus.

measured before and after wetting. Following testing, specimens were oven-dried at 100 °C for 5 h to determine the content of water and other volatile materials.

Viscoelasticity studies were performed using the modified apparatus of Chen and Lakes [9, 10] (Fig. 2). One end of the specimen was clamped to the rigid framework and a high-intensity neodymium iron boron magnet and mirror were clamped to the other end. Specimens were clamped rather than glued because wet bamboo was to be examined and the properties of wet glue tend to degrade. The mass of the clamp assembly lowered the maximum resonant frequency from about 10 kHz in torsion to about 1 kHz. A sinusoidal voltage from a digital function generator was applied to the Helmholtz coil which, in turn, caused an axial torque on the magnet, giving rise to torsion of the specimen. Angular displacement was measured using the following method. Light from a helium neon laser was reflected from the specimen's mirror to a split-diode light detector. The output from the detector was applied to a differential amplifier, the action of which was to produce a sinusoid in time proportional to the specimen's angular displacement. To achieve bending, the Helmholtz coil was rotated by 90° and the motion of the reflected light beam was also rotated by 90° by passing it through a dove prism oriented at 45° with respect to the horizontal.

Frequency was recorded from the function generator and the phase between stress and strain was measured from the width of a Lissajous figure. At frequencies approaching the specimen's first torsional resonance, stiffness and damping were calculated by numerical solution of an exact relationship for the torsional behaviour of a viscoelastic cylinder [9, 10]. At resonance, damping was calculated using the shape of the frequency response curve near the resonance (the resonance half-width method)

$$\tan\delta \approx \frac{1}{3}\frac{\Delta\omega}{\omega_0} \qquad (1)$$

where $\Delta\omega$ is the full-width of the resonance curve at half-maximum amplitude.

Each specimen was tested at audio and sub-audio frequencies at a temperature of 22 °C. In most experiments, input voltage (and thus maximum stress) was held constant. The maximum outer fibre strain was always less than 1 microstrain (10^{-6}), thus ensuring linear damping.

3. Results and discussion

Moduli and loss tangents of dry bamboo microsamples are shown in Figs 3 and 4. The loss tangent was relatively small and exhibited little variation with frequency; it was somewhat greater in torsion than in bending. Moduli varied little with frequency, a fact which, by virtue of the Kramers Kronig relation, is consistent with the relatively small value of loss tangent. Loss tangent values for dry bamboo were of similar magnitude to values reported by others for wood [3]. The bamboo exhibited evidence of anisotropy, in that Young's modulus was substantially greater than the shear modulus.

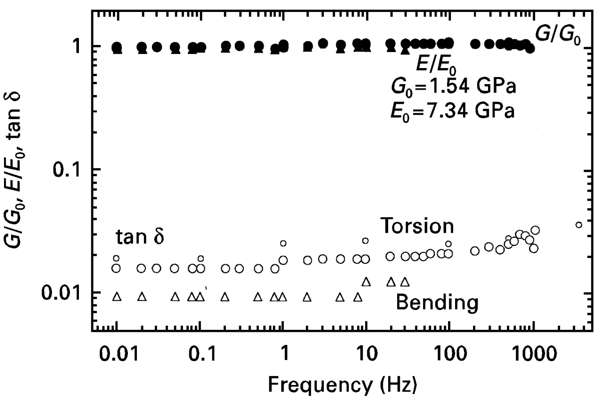

Figure 3 Viscoelastic properties of dry bamboo sample 1, lower density, 0.86 $g\,cm^{-3}$, in torsion and bending. Normalized stiffness and mechanical damping versus frequency. $G_0 = 1.54$ GPa, $E_0 = 7.34$ GPa. RH 45%.

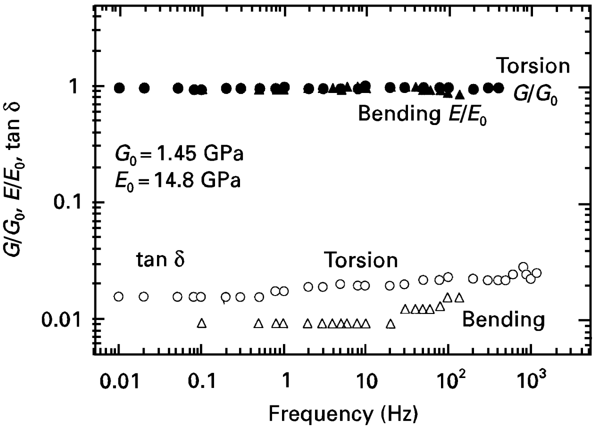

Figure 4 Viscoelastic properties of dry bamboo sample 2, higher density, 1.08 $g\,cm^{-3}$, in torsion and bending. Normalized stiffness and mechanical damping versus frequency. $G_0 = 1.45$ GPa, $E_0 = 14.8$ GPa. RH 45%.

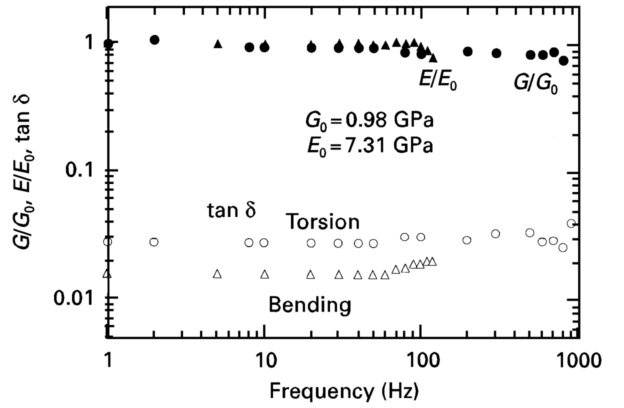

Figure 5 Viscoelastic properties of wet bamboo sample 1, lower density, 1.16 $g\,cm^{-3}$, in torsion and bending. Normalized stiffness and mechanical damping versus frequency. $G_0 = 0.98$ GPa, $E_0 = 7.31$ GPa.

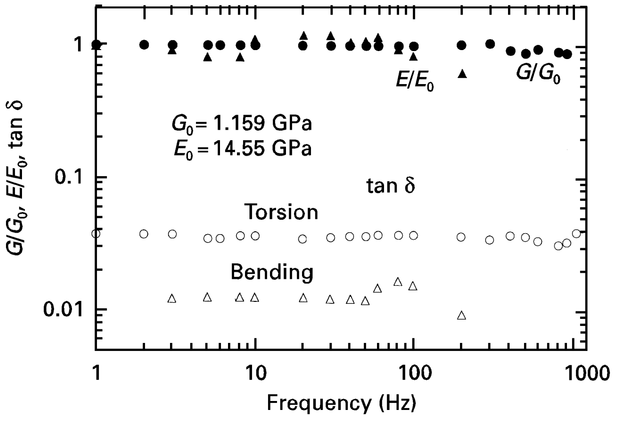

Figure 6 Viscoelastic properties of wet bamboo sample 2, higher density, 1.25 $g\,cm^{-3}$, in torsion and bending. Normalized stiffness and mechanical damping versus frequency. $G_0 = 1.16$ GPa, $E_0 = 14.55$ GPa.

For wet bamboo, the viscoelastic behaviour is shown in Figs 5 and 6. In torsion, the loss tangent of wet bamboo was greater than that of dry bamboo by a factor of 1.5–2; in bending, wet bamboo was higher in loss by a factor of 1.2–1.5. Moreover, the transition from room humidity to the fully hydrated condition caused a transverse expansion of about 2% and an axial contraction of about 0.1%. Weight changes from the fully wet to the oven-dry condition indicate a water content of 43% for specimen 1 and 24% for specimen 2 when wet. By contrast, wood [8] when green has about 30% moisture content, and drying to 10% moisture causes a lateral shrinkage of 3%–4.2%.

Results may be evaluated in the light of viscoelastic composite theory. Viscoelastic composites [11], with phases which are linearly viscoelastic, have effective relaxation and creep functions which can be obtained by the correspondence principle of the theory of linear viscoelasticity [12–15] provided that an analytical solution is available for the elastic behaviour. In some cases, explicit results in terms of linear viscoelastic matrix properties are known, and thus permit direct use of experimental information [16]. In composites of biological origin, phase properties are seldom well known, so that inferences are necessarily indirect [17]. Even so, in bone, a complex natural composite, it has been demonstrated that the ground substance at the interface between osteons, which are large longitudinal fibres in bone, is compliant [18], viscous-like [19] and weak [20]. Viscoelastic composites with aligned fibres are comparatively simple in the relation between constituent properties and composite properties. Uniaxial tension behaviour is governed primarily by the fibre properties, assuming that they are stiff. For a two-phase elastic material with aligned fibres, the Voigt relation applies

$$E_c = E_1 V_1 + E_2 V_2 \tag{2}$$

in which E_c, E_1 and E_2 refer to the Young's modulus of the composite, phases 1 and 2, and V_1 and V_2 refer to the volume fraction of phases 1 and 2 with $V_1 + V_2 = 1$. Use of the correspondence principle gives, for a viscoelastic composite,

$$E_c^* = E_1^* V_1 + E_2^* V_2 \tag{3}$$

with $E^* = E' + \mathrm{i}\,E''$ and loss tangent $\tan\delta = E''/E'$. Taking the ratio of real and imaginary parts, the loss tangent $\tan\delta_c = E_c''/E_c'$ of the Voigt composite is given by

$$\tan \delta_c = (V_1 \tan \delta_1 + V_2 \frac{E'_2}{E'_1} \tan \delta_2)/(V_1 + \frac{E'_2}{E'_1} V_2) \quad (4)$$

Torsion behaviour is more matrix-dominated. For a two-phase Reuss viscoelastic composite

$$\frac{1}{G^*_c} = \frac{V_1}{G^*_1} + \frac{V_2}{G^*_2} \quad (5)$$

the Reuss loss tangent is, with J as the compliance

$$\tan \delta_c = (V_1 \tan \delta_1 + V_2 \frac{J'_2}{J'_1} \tan \delta_2)/(V_1 + \frac{J'_2}{J'_1} V_2) \quad (6)$$

In a unidirectional fibrous composite with stiff fibres and a compliant matrix, the tensile or bending properties are dominated by the fibres, while the torsional properties are dominated by the matrix. The actual properties of bamboo are not indicative of such simplicity of structure: there is considerable anisotropy in stiffness and less anisotropy in damping.

Cellular solids [21] are composite materials in which one phase is empty space or a fluid, such as air or water. Cellular solids include honeycombs, foams and other porous materials as well as natural materials such as wood, bone, and bamboo. The correspondence principle may then be applied to the foam as a composite with one mechanically active phase. Under such circumstances the loss tangent of the cellular solid is the same as that of the solid from which it is made, assuming that the solid phase in homogeneous form is chemically identical to the solid phase in the cellular solid

$$\tan \delta_c = \tan \delta_{solid}. \quad (7)$$

Therefore anisotropy in the damping cannot come from anisotropy in the porosity alone. Implications are discussed below.

Biological composite materials such as bone, tendon, and wood have a complex hierarchical structure [22], as does bamboo. Bamboo has both fibrous and cellular structural features, aligned with the stem axis [4]. The observed anisotropy in the stiffness is a consequence of this alignment. The anisotropy was greater in the denser bamboo sample ($1.08\ g\,cm^{-3}$), $E/G = 10.2$, than in the sample of lower density ($0.86\ g\,cm^{-3}$), $E/G = 4.87$. For comparison, an isotropic material with a Poisson's ratio of 0.3 has $E/G = 2.6$. The density may be compared with wood, which varies over a wide range from 0.1 to $\sim 1\ g\,cm^{-3}$ [21]. The solid component of the cell walls in wood has a density of $1.5\ g\,cm^{-3}$ and a stiffness of $E = 35$ GPa [21]. So, in comparing the density, this bamboo corresponds to the densest of woods. For comparison, the range of density quoted for a variety of bamboos of moisture content 12% is $0.4–1.08\ g\,cm^{-3}$ with the lowest density in the inner regions [23] adduced in [24]; the tan δ for bending vibration was from 0.012–0.022, in the same range as the present results.

The difference in anisotropy with density in the bamboo is attributed to the greater number of bundle sheaths in the denser bamboo [5]; these appear as fibre-like structures in optical micrographs. However, there is not so much anisotropy in the damping: tan δ in torsion and bending differ by less than a factor of two. Even so, the anisotropy in damping cannot be caused by orientation in the porosity because a cellular solid with one solid phase, while it may be anisotropic in stiffness, must have the same tan δ as the solid phase, in the absence of dynamic fluid flow effects, which are not operative in dry bamboo. Anisotropy in damping can arise from large-scale molecular orientation effects or from the presence of at least two distinct solid phases.

Viscoelastic damping may be regarded as a consequence of molecular motions in the biopolymer constituents, specifically cellulose and lignin [5], of the bamboo. Because the damping is relatively small, and exhibits no significant peaks, one may conclude that the molecular chains are highly constrained. Moreover, because there is not much effect of wetting, water does not plasticize the polymer chains, again suggesting a highly constrained molecular organization. The absence of a significant damping peak in bending indicates a minor role for fluid flow processes in the damping of bamboo.

The behaviour of synthetic polymer matrix composite materials may be considered for comparison. The viscoelastic behaviour of the composite as a whole depends on the stress experienced by the matrix, which, being a polymer, exhibits much more viscoelasticity than the graphite fibres [25]. Consequently, polymer matrix unidirectional fibre composites creep very little if they are loaded along the direction of the fibres, and creep considerably more if loaded transversely or in shear. For laminates built up of fibrous layers, fibre-dominated graphite–epoxy layups such as $\{0\}_{48}$ and $\{0/45/0/-45\}_{6s}$ exhibited little viscoelastic response and little redistribution of strain due to creep [26]. By contrast, matrix-dominated layups, such as $\{90\}_{48}$ and $\{90/-45/90/-45\}_{6s}$, exhibited significant creep and strain redistribution.

Bamboo has many structural features which may be regarded as optimal in an engineering sense. For example, the tubular structure itself provides good structural stiffness per unit weight. The nodes behave as bulkheads and prevent buckling of the stem under compression [27].

4. Conclusion

Damping, measured by tan δ, in dry bamboo was about 0.01 in bending and 0.02–0.03 in torsion, with little dependence on frequency in the audio range. Wet bamboo exhibited somewhat greater tan δ: 0.012–0.015 in bending and 0.03–0.04 in torsion. The anisotropy in damping implies a purely cellular model is insufficient; there is large-scale molecular orientation or at least two distinct solid phases.

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References

1. R. J. THOMAS, in "Wood structure and composition", edited by M. Lewin and I. S. Goldstein (Marcel Dekker, New York, 1991).
2. L. KNOPOFF, in "Physical Acoustics", Vol. 3b, edited by E. P. Mason (Academic Press, New York, 1965) pp. 287–324.
3. C. A. WERT, M. WELLER and D. CAULFIELD, *J. Appl. Phys.* **56** (1984) 2453.
4. S. AMADA, *MRS Bull.* **20** (1995) 35.
5. S. AMADA, T. MUNEKATA, Y. NAGASE, Y. ICHIWAKA, A. KIRIGAI and Y. ZHIFEI, *J. Compos. Mater.* **30** (1996) 800.
6. S. JAIN, R. KUMAR and U. C. JINDAL, *J. Mater. Sci.* **27** (1992) 4598.
7. R. SUMMITT and A. SLIKER (eds.), "CRC Handbook of Materials Science", Vol. IV, "Wood" (CRC Press, Boca Raton, FL, 1980).
8. C. SKAAR, "Water in Wood" (Syracuse University Press, Syracuse, NY, 1972).
9. C. P. CHEN and R. S. LAKES, *J. Rheol.* **33** (1989) 1231.
10. M. BRODT and R. S. LAKES, *Rev. Sci. Instrum.* **66** (1995) 5292.
11. Z. HASHIN, *J. Appl. Mech.* **50** (1983) 481.
12. *Idem*, *J. Appl. Mech. Trans. ASME* **32E** (1965) 630.
13. R. A. SCHAPERY, *J. Compos. Mater.* **1** (1967) 228.
14. R. M. CHRISTENSEN, "Mechanics of composite materials" (Wiley, New York, 1979).
15. *Idem*, *J. Mech. Phys. Solids* **17** (1969) 23.
16. Z. HASHIN, *AIAA J.* **4** (1966) 1411.
17. J. L. KATZ, *J. Biomech.* **4** (1971) 455.
18. *Idem*, *Nature* **283** (1980) 106.
19. R. S. LAKES and S. SAHA, *Science* **204** (1979) 501.
20. K. PIEKARSKI, *J. Appl. Phys.* **41** (1970) 215.
21. L. J. GIBSON and M. F. ASHBY, "Cellular solids" (Pergamon, Oxford, 1988).
22. R. S. LAKES *Nature* **361** (1993) 511.
23. S. MAMADA and Y. KAWARUMA, *Mokuzai Gakkaishi* (*J. Jpn Wood Res. Soc.*) **19** (1973) 555.
24. J. JANSSEN, "Mechanical Properties of Bamboo" (Kluwer, Dordrecht, 1991).
25. J. B. STURGEON, in "Creep of Engineering Materials", edited by C. D. Pomeroy (Mechanical Engineering Publications, London, 1978) p. 175.
26. M. E. TUTTLE and D. L. GRAESSER, *Opt. Lasers Eng.* **12** (1990) 151.
27. J. E. GORDON, "Structures" (Penguin, Harmondsworth, UK, 1983) pp. 294 ff.

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