Cryogenically Cooled Sapphire–Rutile Dielectric Resonators for Ultrahigh-Frequency Stable Oscillators for Terrestrial and Space Applications

Michael Edmund Tobar, *Member, IEEE*, John Gideon Hartnett, Eugene N. Ivanov, Dominique Cros, Pierre Blondy, and Pierre Guillon, *Senior Member, IEEE*

***Abstract*—The highest short-term frequency-stable microwave resonator oscillators utilize liquid-helium-cooled sapphire dielectric resonators. The temperature coefficient of frequency of such resonators is very small due to residual paramagnetic impurities canceling the temperature coefficient of permittivity (TCP). At higher temperatures, which are accessible in space or with liquid nitrogen, the effect is too weak, and if extra impurities are added, the loss introduced is too great. An alternative technique involves using two low-loss dielectric materials with TCP of opposite sign. Following this approach, a sapphire–rutile resonator was designed with mode frequency-temperature turning points between 50–80 K, with Q-factors of order 10^7. Previous designs used thin disks of rutile fixed to the ends of the sapphire cylinder. Due to the high permittivity of rutile, such resonators have a high density of spurious modes. By placing rings at the end faces instead of disks, the majority of the spurious modes are raised above the operation frequency and the requirement for thin disks is removed. Finite-element analysis has been applied and compares well with experiment. The application to the design of high stability "fly-wheel" oscillators for atomic frequency standards is discussed.**

***Index Terms*—Dielectric resonator, frequency stable, rutile, sapphire.**

I. Introduction

LOW-NOISE high-stability resonator-oscillators based on high-quality (Q) sapphire whispering-gallery (WG)-mode resonators have become important devices for telecommunication, radar, and metrological applications. The extremely high-Q factor of sapphire, of 2×10^5 at room temperature, 5×10^7 at liquid nitrogen temperature, and 4×10^9 at liquid-helium temperature has enabled the lowest phase noise [1], [2] and most frequency-stable [3]–[5] oscillators in the microwave regime. To create an oscillator with exceptional frequency stability, the resonator must have the frequency-temperature dependence annulled, as well as a high-Q factor. The temperature coefficient of permittivity (TCP) for sapphire is quite large, and of the order of 10 ppm/K at 77 K. This mechanism allows temperature fluctuations to transform to resonator frequency fluctuations.

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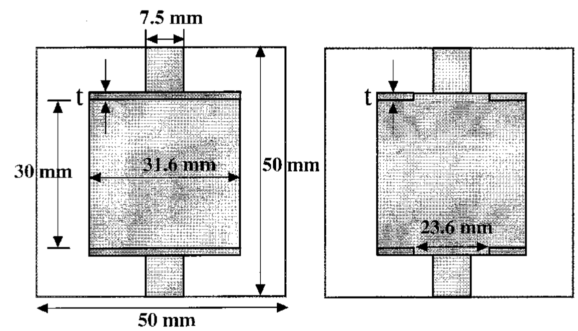

Fig. 1. Sapphire resonator loaded in a metallic cavity, with rutile disks of thickness t, held to the end faces.

The usual electromagnetic technique of annulment is due to the effect of paramagnetic impurities contributing an opposite temperature coefficient (due to magnetic susceptibility) compared to the TCP. This technique has only been realized successfully in liquid-helium environments [6]–[8]. It is important to raise this temperature of compensation to 40–80 K if this technology is to be developed for space applications and for liquid-nitrogen-cooled devices. To raise the temperature of annulment, large concentrations of paramagnetic impurities are required, which, in turn, significantly degrades the Q-factor [9]. Recently, a new technique incorporating dielectric compensation to a WG sapphire resonator has been developed [10], [11]. The method consists of placing two dielectric disks at the end of the sapphire cylinder, as shown in Fig. 1. A similar technique has also been implemented to compensate low-order modes in high-temperature superconducting resonators [12], [13]. A good choice of compensating material is rutile, which has low loss and an opposite sign of TCP [14], [15]. Other materials such as strontium titanate have been studied [10]. However, it introduces more loss than rutile and its large dielectric permittivity requires the thickness of the dielectric layers to be of the order of micrometers, which is not practical [16].

The values of TCP for sapphire and rutile have been measured accurately from 300 K to below 10 K [15], [17], and we use

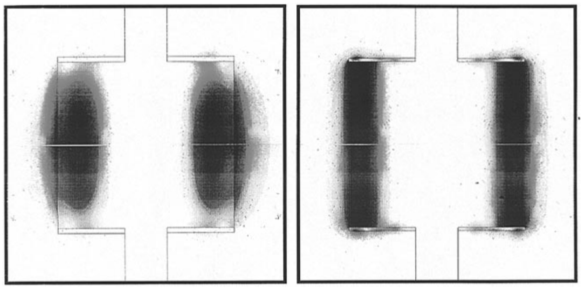

Fig. 2. Magnitude of the mode electric-field density. (a) $\mathrm{WGE}_{8,0,0}$ mode. (b) $\mathrm{WGH}_{10,0,0}$ mode. The outer border shows the position of the metallic enclosure.

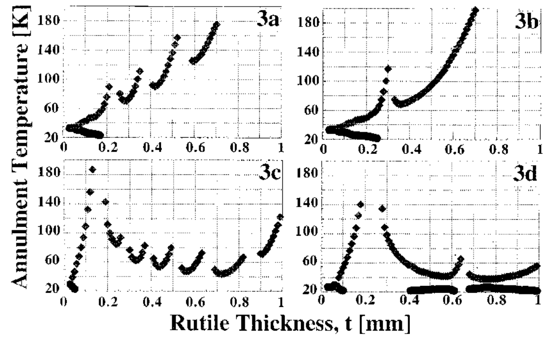

Fig. 3. Annulment temperature versus thickness for various modes. (a) $\mathrm{WGH}_{10,0,0}$ ($N1_{10}$) and $\mathrm{WGH}_{10,0,2}$ ($N2_{10}$) modes with disks of rutile fixed to the end faces. (b) $\mathrm{WGH}_{10,0,0}$ ($N1_{10}$) mode with rings rather than disks fixed to the ends. (c) $\mathrm{WGE}_{8,0,0}$ ($S2_8$) mode with disks of rutile fixed to the end faces. (d) $\mathrm{WGE}_{8,0,0}$ ($S2_8$) mode with rings rather than disks fixed to the ends.

these results to calculate the characteristics of a sapphire–rutile resonator as a function of temperature. Dielectric compensation is achieved in a sapphire–rutile composite WG resonator with measured Q-factors of greater than 10^7 at 56 K and greater than 10^6 at 75 K.

From this result and state-of-the-art frequency stabilization circuitry, we demonstrate that current technology is suitable for the construction of an ultra-stable oscillator with fractional frequency instability of order 10^{-14}. This is the "fly-wheel" oscillator requirement necessary for an atomic fountain or cold atom clock to reach the performance set by the quantum limit [18]. Even though a liquid-helium-cooled clock has two orders of magnitude better stability [5], the liquid-nitrogen clock is more easily transportable and much cheaper to maintain. The oscillators based on composite dielectric resonators can also be considered for use as fly-wheel oscillators for space applications (such as the Atomic Clock Ensemble in Space (ACES) project on board the International Space Station). State-of-the-art quartz oscillators are an order of magnitude worse ($\sim 10^{-13}$) and limit the performance of an atomic clock due to the Dick effect [19], [20].

II. Composite Resonator Properties

A. Finite-Element Analysis

Rigorous analysis of 12-GHz modes in the structure (see Fig. 1) was achieved by implementing finite-element software developed at the Research Institute on Microwave and Optical Communication (IRCOM), Limoges, France, specifically designed to solve resonant anisotropic dielectric systems [21]. We analyzed the frequency-temperature behavior of the $\mathrm{WGH}_{10,0,0}$ (or $N1_{10}$) and the $\mathrm{WGE}_{8,0,0}$ ($S2_8$) modes. The WG notation is the same as introduced at IRCOM [22], and the N-S notation means nonsymmetric (or antisymmetric) and symmetric magnetic field in the axial direction, respectively, and the following number denotes the ascending order in frequency [17], [23]. The electric-field density plots are shown in Fig. 2, and the annulment temperature versus thickness graphs are shown in Fig. 3.

To calculate the frequency-temperature dependence, the anisotropic permittivity and expansion coefficients of sapphire and rutile need to be known as a function of temperature [15], [17]. Using these values, an automatic program was written to calculate the frequency of the resonator as a function of temperature at intervals of 2.5 K between 20–62.5 K and intervals of 10 K above 70 K. A polynomial fit was then applied to this data to find the annulment temperature. This procedure was carried out for rutile thickness between 0.03–1.0 mm, and the results of calculations are plotted in Fig. 3.

All the frequencies of the analyzed modes were close to 12 GHz at cryogenic temperatures. The frequency of the same mode in the composite resonator in comparison to the bare sapphire resonator was higher for WGE modes as the axial boundary condition at the sapphire–rutile interface causes the field to be squashed further into the sapphire (a Bragg effect). Conversely, the frequency is lower in the WGH modes as the axial boundary conditions cause the field to be stretched by the rutile disks due to the larger permittivity of rutile.

In general, for a small thickness of rutile ($\sim$0.03 mm) there is not enough rutile to fully compensate the resonator. Instead, a point of inflection occurs at about 20–30 K for both WGE and WGH modes. When the thickness gets large enough (see Fig. 3), the inflection point turns into an annulment point and separates in two. At the point of separation, the second derivative is matched as well as the first and a flat annulment point of zero curvature is created. At larger values of thickness, excess spurious modes exist due to modes mainly in the rutile. To lessen the spurious-mode density, we introduced rings (with an inner diameter of 23.6 mm) held to the ends. This had the effect of tuning the spurious rutile modes to higher frequencies with correspondingly larger frequency separations, and reduced the effect. However, the effect of the spurious modes on WGE and WGH modes are significantly different. Thus, we describe them separately in the Sections II-B and -C.

B. Temperature Characteristics for WGE Modes

Fig. 3(c) and (d) shows the annulment temperature versus thickness for the $\mathrm{WGE}_{8,0,0}$ mode. The rutile acts to only perturb the resonant frequency when the thickness is less than about 0.12 mm. This is the linear regime where the annulment temperature is proportional to the thickness. However, at about 0.12 mm in the disk structure and 0.15 mm in the ring structure, a spurious mode starts to interact with the sapphire $\mathrm{WGE}_{8,0,0}$ mode. This spurious mode ($\mathrm{WGE}_{8,0,0}$ in rutile) interacts due to

TABLE I
COMPARISON OF EXPERIMENTAL RESULTS WITH FINITE-ELEMENT CALCULATION

Mode	Measured frequency at annulment temp. [GHz]	Predicted frequency at annulment temp. [GHz]	Measured annulment temp. [K]	Predicted annulment temp. [K]	Measured curvature [ppm/K^2]	Predicted curvature [ppm/K^2]	Measured Q-factor [10^6]
WGE_8	12.031	12.071	55	54	0.0365	0.0395	4
WGH_{10}	11.916	11.947	72	76	0.44	0.37	6

the tangential boundary conditions, which require the transverse electric field between the rutile and sapphire to be continuous.

After the thickness becomes large enough, the rutile mode is tuned lower in frequency than the $\mathrm{WGE}_{8,0,0}$ mode and the annulment temperature starts to decrease in temperature. The rutile disks can support many WG modes, and in the range of thickness from 0 to 1 mm, five more spurious-mode interactions exist. If we substitute the disk for a ring structure, the frequency and separation of these modes are raised high enough that only one spurious mode remains out of the five.

It is interesting to note if we ignore the interacting WG modes in rutile, the temperature versus thickness characteristic with the disk and ring in Fig. 3(c) and (d) are very similar. The first resonance due to rutile occurs only at a slightly different thickness, unlike the rutile WG modes, which are shifted greatly. Also, a local minimum in the annulment temperature-thickness characteristic occurs in both cases close to 0.75 mm. This suggests an effect that is due to the boundary condition of the WGE mode at the sapphire–rutile interface. The WGE modes are quasi-TE and, hence, have the majority of the electric field tangential to this boundary. Thus, WGE modes in the rutile and sapphire couple strongly. This phenomenon is a manifestation of the Bragg effect [24].

C. Temperature Characteristics for WGH Modes

WGH modes are quasi-TM, therefore, the majority of the electric field is normal to the sapphire–rutile boundary and the modes do not couple strongly to the new Bragg modes. Inspecting Fig. 3(a) and (b) closely, small kinks at 0.12 mm in (a) and 0.15 mm in (b) are present. This is due to the small hybrid TE component coupling to the new Bragg mode. The coupling is too small to see the Bragg effect dominate due to the dominant TM structure. Thus, in general, as the rutile thickness is increased, so does the annulment temperature, as long as the interactions with spurious modes are ignored. When we replace the disk with the ring, three spurious rutile WG modes are reduced to one, in the range of thickness from 0 to 1 mm.

D. Comparison with Experiment

Two rutile rings 0.42-mm thick with an inner diameter of 23.6 mm were held to the ends of the sapphire by sapphire holders incorporating a spring mechanism. Sapphire is the only material that we considered so that the Q-factor would not to be degraded. Measurements of frequency and Q-factor were achieved using standard techniques, similar to those described by Luiten *et al.* [25]. Experimental results and calculation are compared in Table I.

Even though we have not modeled the support system for the rutile rings, results of experiment and finite-element modeling are in good agreement. This shows that finite-element analysis is an excellent technique to design such a resonator for both WGE and WGH modes. This type of resonator is very difficult to model accurately with other techniques. Also, it is important to note, if it was not for the ring structure (rather than a disk structure), the turning point temperature for WGE modes could not have be designed accurately due to the large spurious-mode density without having extremely thin disks. For example, previous results with 0.2-mm thin disks enabled the design of the turning-point temperature for WGH modes, but not WGE modes [26]. In the future, we will calculate complex frequencies to evaluate the Q-factors of composite resonators. It should be noted here that the measured Q-factor of the $\mathrm{WGE}_{8,0,0}$ mode is degraded due to the influence of a nearby spurious mode, which also slightly reduces the curvature. The $\mathrm{WGE}_{9,0,0}$ mode has been measured at 13 GHz (but not modeled) and also had a compensation point close to 55 K with a Q-factor of 30 million. This result is evidence that the Q-factor of the $\mathrm{WGE}_{8,0,0}$ mode should be of the order of 10^7 if the nearby mode did not degrade the performance. The mode is believed to be coupled to the support structure and, with redesign, we anticipate an improved Q-factor for this mode.

III. OSCILLATOR PERFORMANCE CONSIDERATIONS

A. Stabilization of Frequency Variations Due to Electronic Noise

It is customary to characterize the frequency instability of an oscillator by the square root of Allan variance (SRAV) σ_y [27]. This is the primary measure of oscillator frequency instability in the time domain. Taking the minimum value of σ_y and multiplying it by the resonator Q-factor, $\delta = \sigma_y^{\min} Q$, another characteristic of an oscillator frequency stability, termed the line splitting factor, is defined. Assuming the oscillator is frequency stabilized with a frequency noise suppression system, the line splitting factor can be interpreted as fraction of the resonator bandwidth within which the oscillator remains locked, with respect to the center of resonance.

Our goal is to build a microwave oscillator with a short-term frequency instability of order 10^{-14}. This is a necessary requirement to achieve the potential of a typical atomic Cs fountain or cold atom frequency standard for space applications. The University of Western Australia (UWA) sapphire clock has been locked with a line splitting factor of 10^{-7} to obtain an instability of order 10^{-16} [5]. The Jet Propulsion Laboratory (JPL) 87K mechanically temperature compensated clock also locked with a line splitting factor of 10^{-7} to obtain a stability of 10^{-13} [28]. The voltage noise floor in an optimized Pound frequency discriminator was measured and the SRAV calculated. For a resonance with a Q-factor of 10^7, the measurements translate to a discriminator noise floor of 3×10^{-15} from 1 to 10 s of averaging time, rising to 3×10^{-14} at 100 s, which is suitable for an atomic frequency standard.

B. Stabilization of Frequency Variations Due to Temperature Changes

A copper cavity, in an evacuated can of a design similar to the liquid helium clock, was cooled to 77 K by liquid nitrogen and fractional temperature fluctuations were measured. Based on the results and the curvature at the annulment point of $2 \times 10^{-7}/\mathrm{K}^2$, the SRAV due to temperature fluctuations, was calculated to be 1.5×10^{-15} at 1 s rising to 3×10^{-14} at 30 s of averaging time. This assumes a temperature control maintaining the resonator within a 100 $\mu \cdot$ K of the turning point, which is achievable with current temperature control technology. This calculation, however, was without active temperature control, which, when implemented, will even further reduce this source of noise.

IV. Conclusion

One would prefer the rutile to act solely perturbatively on the sapphire resonator. Clearly this does not always occur. However, our analysis clearly shows how to avoid resonant effects, as well as furnish an understanding of the modes in such a structure. Specifically, we have shown, by holding rutile rings to the end faces of a cylindrical sapphire resonator, good designability of the annulment temperature above 30 K can be achieved with a low spurious-mode density. These temperatures are easily accessible by closed-cycle refrigerators, liquid nitrogen, and radiative coolers for space applications. Also, we have shown that a frequency-stabilized oscillator based on this resonator has the potential to pump an atomic frequency standard at the quantum limit.

References

[1] M. E. Tobar and D. G. Blair, "Phase noise analysis of the sapphire loaded superconducting niobium cavity oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 344–347, Feb. 1994.

[2] E. N. Ivanov, M. E. Tobar, and R. A. Woode, "Applications of interferometric signal processing to phase noise reduction in microwave oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1537–1545, Oct. 1998.

[3] A. J. Giles, A. G. Mann, S. K. Jones, D. G. Blair, and M. J. Buckingham, "A very high stability sapphire loaded superconducting cavity oscillator," *Phys. B*, vol. 165, pp. 145–146, 1990.

[4] A. N. Luiten, A. G. Mann, and D. G. Blair, "Power stabilized exceptionally high stability cryogenic sapphire resonator oscillator," *IEEE Trans. Instrum. Meas.*, vol. 44, pp. 132–135, Apr. 1995.

[5] S. Chang, A. G. Mann, and A. N. Luiten, "Improved cryogenic sapphire oscillator with exceptionally high frequency stability," *Electron. Lett.*, submitted for publication.

[6] S. K. Jones, D. G. Blair, and M. J. Buckingham, "The effects of paramagnetic impurities on the frequency of sapphire loading superconducting resonators," *Electron. Lett.*, vol. 24, pp. 346–347, 1988.

[7] A. G. Mann, A. J. Giles, D. G. Blair, and M. J. Buckingham, "Ultra-stable cryogenic sapphire dielectric microwave resonators: Mode frequency-temperature compensation by residual paramagnetic impurities," *J. Phys. D, Appl. Phys.*, vol. 25, pp. 1105–1109, 1992.

[8] A. N. Luiten, A. G. Mann, and D. G. Blair, "Paramagnetic susceptibility and permittivity measurements at microwave frequencies in cryogenic sapphire resonators," *J. Phys. D, Appl. Phys.*, vol. 29, pp. 2082–2090, 1996.

[9] J. G. Hartnett, M. E. Tobar, A. G. Mann, E. N. Ivanov, J. Krupka, and R. Geyer, "Frequency-temperature compensation in Ti^{3+} and Ti^{4+} doped sapphire whispering gallery mode resonators," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 46, pp. 993–1000, July 1999.

[10] M. Tobar, J. Krupka, R. Woode, and E. Ivanov, "Dielectric frequency-temperature compensation of high quality sapphire dielectric resonators," in *Proc. IEEE Int. Freq. Contr. Symp. Dig.*, 1996, pp. 799–806.

[11] M. E. Tobar, J. Krupka, J. G. Hartnett, E. N. Ivanov, and R. A. Woode, "sapphire–rutile frequency-temperature compensated whispering gallery microwave resonators," in *Proc. IEEE Int. Freq. Contr. Symp. Dig.*, 1997, pp. 1000–1008.

[12] N. Klein, A. Scholen, N. Tellmann, C. Zuccaro, and K. W. Urban, "Properties and applications of HTS-shielded dielectric resonators: a state-of-the-art-report," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1369–1373, July 1996.

[13] J. Gallop, L. Hao, F. Abbas, and C. D. Langham, "Frequency stability of dielectric loaded HTS microwave resonators," *IEEE Trans. Appl. Superconduct.*, vol. 7, pp. 3504–3507, June 1997.

[14] N. Klein, C. Zuccaro, U. Dahne, H. Schulz, and N. Tellmann, "Dielectric properties of rutile and its use in high temperature superconducting resonators," *J. Appl. Phys.*, vol. 78, pp. 6683–6686, 1995.

[15] M. Tobar, J. Krupka, E. Ivanov, and R. Woode, "Anisotropic complex permittivity measurements of mono-crystalline rutile between 10-300 kelvin," *J. Appl. Phys*, vol. 83, pp. 1604–1609, 1998.

[16] J. G. Hartnett, M. E. Tobar, A. G. Mann, E. N. Ivanov, J. Krupka, S. N. Jacobson, L. Madsen, and U. Helmerson, "Electromagnetic frequency-temperature compensation techniques for high-Q sapphire resonators.," in *Proc. Asia–Pacific Microwave Conf.*, 1998, pp. 159–162.

[17] J. Krupka, K. Derzakowski, A. Abramowicz, M. E. Tobar, and R. Geyer, "Whispering gallery modes for complex permittivity measurements of ultra-low loss dielectric materials," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 752–759, June 1999.

[18] G. Santarelli, P. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon, "Quantum projection noise in an atomic fountain: A high stability cesium frequency standard," *Phys. Rev. Lett.*, pp. 4619–4622, 1999.

[19] G. J. Dick, "Local oscillator induced instabilities in trapped ion frequency standards," in *Proc. Precise Time and Time Interval*, Redondo Beach, CA, 1987, pp. 133–147.

[20] G. Santarelli, C. Audoin, A. Makdissi, P. Laurent, G. J. Dick, and A. Clarion, "Frequency stability degradation of an oscillator slaved to a periodically interrogated atomic resonator," *IEEE Trans. Utrason., Ferroelect, Freq. Contr.*, vol. 45, pp. 887–894, July 1998.

[21] M. Aubourg and P. Guillon, "A mixed finite element formulation for microwave device problems: Application to MIS structure," *J. Electromag. Waves Applicat.*, vol. 45, pp. 371–386, 1991.

[22] P. Guillon and X. Jiao, "Resonant frequencies of whispering gallery dielectric resonators modes," *Proc. Inst. Elect. Eng.*, pt. H, vol. 134, pp. 497–501, 1987.

[23] J. Krupka, D. Cros, A. Luiten, and M. Tobar, "Design of very high-Q sapphire resonators," *Electron. Lett.*, vol. 32, pp. 670–671, 1996.

[24] C. J. Maggiore, A. M. Clogston, G. Spalek, W. C. Sailor, and F. M. Mueller, "Low-loss microwave cavity using layered dielectric materials," *Appl. Phys. Lett.*, vol. 64, pp. 1451–1453, 1994.

[25] A. N. Luiten, A. G. Mann, and D. G. Blair, "High resolution measurement of the temperature-dependence of the Q, coupling and resonant frequency of a microwave resonator," *IOP Meas. Sci. Technol.*, vol. 7, pp. 949–953, 1996.

[26] M. E. Tobar, J. G. Hartnett, D. Cros, P. Blondy, J. Krupka, E. N. Ivanov, and P. Guillon, "Design of high-Q frequency-temperature compensated dielectric resonators," *Electron. Lett.*, vol. 35, pp. 303–305, 1999.

[27] D. W. Allan, "Time and frequency (time domain) characterization, estimation, and prediction of precision clocks and oscillators," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. UFFC-34, pp. 647–654, Nov. 1987.

[28] D. G. Santiago, G. J. Dick, and R. T. Wang, "Frequency stability of 10^{-13} in a compensated sapphire oscillator operating above 77 K," in *Proc. IEEE Int. Freq. Cont. Symp. Dig.*, 1996, pp. 772–775.

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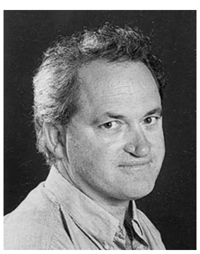

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