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This Week's Citation Classic

Schulz-DuBois E O. Paramagnetic spectra of substituted sapphires—part I: ruby. *Bell Syst. Tech. J.* **38**:271-90, 1959.
[Bell Telephone Laboratories, Murray Hill, NJ]

This paper describes the electron spin resonance spectrum of chromium ions in ruby. The spin Hamiltonian is diagonalized by numerical computations. The energy levels and the expansion coefficients of the quantum states are plotted as functions of the DC magnetic field and its orientation. From these data one has all spin resonance transitions and their responses to radio frequency magnetic field polarization. Several predictions of the computations are checked by experiments. [The *SCI*® indicates that this paper has been cited in over 100 publications since 1961.]

Erich O. Schulz-DuBois
Institute of Applied Physics
University of Kiel
D-2300 Kiel 1
Federal Republic of Germany

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"In 1957, I joined Derek Scovil's group at Bell Laboratories. He, together with Harold Seidel and George Feher, had just demonstrated the first solid state maser[1] based on Nico Bloembergen's three-level proposal.[2] Their active material was gadolinium ethyl sulfate, objectionable not so much because of its alcoholic content but because of its mechanical softness. Ruby, i.e., chromium substituted aluminium oxide, looked like a better material.

"Derek asked me to compile ruby resonance data for design information on possible three-level operating conditions. This was the first time that I put quantum theory to practical use. The spin Hamiltonian constants were measured by Joe Geusic,[3] then at Ohio State University. My calculation started with a coordinate transformation to conditions suitable for work with electromagnetic slow-wave structures. In the diagonalization calculation, I was helped by a little old lady, Marion Gray, one of Bell's finest mathematicians at that time. She also obtained particular analytical results. Some of the computed results were checked by experiments. The complete memo was used in our laboratory for about a year prior to publication. Related work was done at that time by Chihiro Kikuchi's group at Michigan[4] and by William Chang and Tony Siegman at Stanford.[5]

"This paper has been highly cited for several reasons. Our subsequent development of the ruby traveling-wave maser[6] proved this to be the lowest noise microwave receiver anywhere. It made satellite communications economically feasible, it doubled the range of anti-ICBM radars, and it permitted the Nobel prizewinning discovery of the cosmic background radiation.[7] The priority given to maser development for these purposes made me break my promise: parts II and III of this paper were never written. Originally I had planned to study Co^{++} and Fe^{+++} spectra in order to find rapidly relaxing coincident transitions based on Bloembergen's cross-relaxation mechanism.[8,9]

"I received requests for reprints of this paper from all those who worked on ruby. After my reprints were exhausted, further requests were served by Bell's monograph department. The paper was reproduced several times as a part of books.[10] At universities, e.g., Massachusetts Institute of Technology, the ruby spectrum and my paper were the subject of advanced lab courses.

"Synthetic ruby is a reasonably cheap material. So, for snob appeal, we also measured the spectrum of the much more expensive emerald.[11] For better growth quality of synthetic ruby, development contracts were let to the Linde Company. As a souvenir, I then bought a synthetic star ruby from Linde. This, placed in a ring for my wife, is the only tangible object that still reminds me of the topic of this paper."

1. **Scovil H E D, Feher G & Seidel H.** Operation of a solid state maser. *Phys. Rev.* **105**:762-3, 1957.
2. **Bloembergen N.** Proposal for a new type solid state maser. *Phys. Rev.* **104**:324-7, 1956.
3. **Geusic J E.** Paramagnetic fine structure spectrum of Cr^{+++} in a single ruby crystal. *Phys. Rev.* **102**:1252-3, 1956.
4. **Makhov G, Kikuchi C, Lambe J & Terhune R W.** Maser action in ruby. *Phys. Rev.* **109**:1399-400, 1958.
5. **Chang W S & Siegman A E.** *Characteristics of ruby for maser applications.* Stanford, CA: Stanford University Electronics Laboratory, 1958. Technical Report 156-2.
6. **DeGrasse R W, Schulz-DuBois E O & Scovil H E D.** The three-level solid state traveling-wave maser. *Bell Syst. Tech. J.* **38**:305-34, 1959.
7. **Penzias A A & Wilson R W.** A measurement of excess antenna temperature at 4080 Mc/s. *Astrophysical J.* **142**:419-21, 1965. [Citation Classic. *Current Contents/Physical, Chemical & Earth Sciences* **21**(18):16, 4 May 1981.]
8. **Bloembergen N, Shapiro S, Pershan P S & Artman J O.** Cross-relaxation in spin systems. *Phys. Rev.* **114**:445-59, 1959.
9. **Schulz-DuBois E O, Scovil H E D & DeGrasse R W.** Use of active material in three-level solid state masers. *Bell Syst. Tech. J.* **38**:335-52, 1959.
10. **Orton J W, Paxman D H & Walling J C.** *The solid state maser.* Oxford: Pergamon Press, 1970. 283 p.
11. **Geusic J E, Peter M & Schulz-DuBois E O.** Paramagnetic resonance spectrum of Cr^{+++} in emerald. *Bell Syst. Tech. J.* **38**:291-6, 1959.