Journal of the European Ceramic Society 21 (2001) 2687–2691
www.elsevier.com/locate/jeurceramsoc

Novel dielectric resonator structures for future microwave communication systems

N. Klein*, M. Schuster, S. Vitusevich, M. Winter, H.R. Yi

Forschungszentrum Jülich GmbH, Institut für Schicht- und Ionentechnik, D-52425 Jülich, Germany

Abstract

Recent progress in manufacturing dielectric ceramics and single crystals with low microwave losses is a challenge for the development of novel devices for microwave communication. Device performance is expected to benefit if novel dielectric resonator structures with low loss contribution of the metallic housing would become available. As a first example of novel devices, high-Q quasielliptic filters with application potential for mobile and satellite communication will be presented. We have achieved unloaded quality factors of 30,000 for C-band quasielliptic filters based on BMT including losses associated with the filter housing. The second example is low-phase noise oscillators and secondary frequency standards based on cryogenic whispering-gallery mode resonators machined from sapphire. We have demonstrated an all-cryogenic K-band feedback oscillator for $f = 23$ GHz with phase noise superior to quartz stabilised oscillators. Finally, first ideas about photonic bandgap resonators based on low loss dielectrics will be presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Dielectric properties; Microwave applications; Microwave properties

1. Introduction

In general, the unloaded quality factor Q_0 of a dielectric resonator consists of losses in the dielectric resonator material and in the support structure and of losses in the metallic walls of the shielding cavity:

$$\frac{1}{Q_0} = \kappa \tan \delta + \frac{R_s}{G} \tag{1}$$

In Eq. (1) κ is called the filling factor corresponding to the fraction of electric field energy stored in the dielectric(s) with loss tangent tanδ. The quantity R_s is the surface resistance of the shielding cavity material, which is related to its d.c. resistivity ρ by $R_s = (\omega\mu_0\rho/2)^{1/2}$ ($\omega = 2\pi f$: angular frequency, $\mu_0 = 1.256 \cdot 10^{-6}$ Vs/Am) in case of a normal conducting metal at room temperature. The geometric factor G represents the integral squared amplitude of the rf magnetic field on the inner surface of the shielding cavity.

In order to achieve ultimate Q_0 values either the material or the mode and geometry need to be optimised: the material issues are: (i) improving tanδ of ceramics towards the intrinsic loss contribution by phonons, (ii) device operation at cryogenic temperatures to reduce the intrinsic dielectric losses, (iii) high-temperature superconducting wall segments for reduction of R_s. On the other hand, the geometric factor G is strongly affected by the selected mode and geometry. For cylindrically shaped dielectrics G increases starting from the $\mathrm{HE}_{11\delta}$ dual mode (most relevant for quasielliptic bandpass filters) over the $\mathrm{TE}_{01\delta}$ monomode towards whispering-gallery modes. For the latter, losses in the shielding cavity are negligible. In addition, in multipole filters the parasitic loss contribution due to tuning and coupling elements can be the most severe Q limiting factor.

For the majority of modes in dielectric resonators κ is close to unity, i.e. the field concentration in the dielectric material is very high. Novel structures utilising periodically arranged dielectric elements (photonic crystals) as Bragg reflectors provide a potential to reduce κ significantly and provide high G values at the same time.

2. Novel quasielliptic $\mathrm{HE}_{11\delta}$ filters for satellite and mobile communication

We have developed a novel approach for dielectric dual-mode filters.[1,2] As the main difference in comparison to state-of-the art dielectric dual-mode filter designs

---

* Corresponding author. Tel.: +49-2461-615-722; fax: +49-2461-612-470.

E-mail address: n.klein@fz-juelich.de (N. Klein).

PII: S0955-2219(01)00346-6

we have chosen a resonator and coupling geometry where the metallic losses are very small: originally, this filter concept was developed for dielectric hemispheres but it works also for cylindrically shaped dielectrics. In contrast to the conventionally employed axial arrangement of dielectric resonators coupled by cross-shaped metallic irises we employed a parallel arrangement of dielectric resonators connected by a metallic aperture. In addition, the coupling and tuning elements were arranged in a region where the magnetic field is close to zero. This results in a significantly smaller loss contribution of the shielding cavity. Fig. 1 shows the measured filter characteristic of a quasielliptic four-pole filter employing a BMT ceramic with $\varepsilon_r = 24$ provided by MURATA. The coupling was adjusted for two different values of the bandwidth. The measured Q_0 values were found to be 28,000 for the 1% BW filter (a) and 30,000 for the 0.3% BW filter (b). The measured insertion loss is in very good agreement with the measured unloaded quality factor, if one subtracts 0.1 dB due to attenuation by the input and output coupling antennae. The loss contribution of the employed Murata BMT was found to correspond to a $Q \cdot f$ value equal to 150,000 GHz at 3.7 GHz.

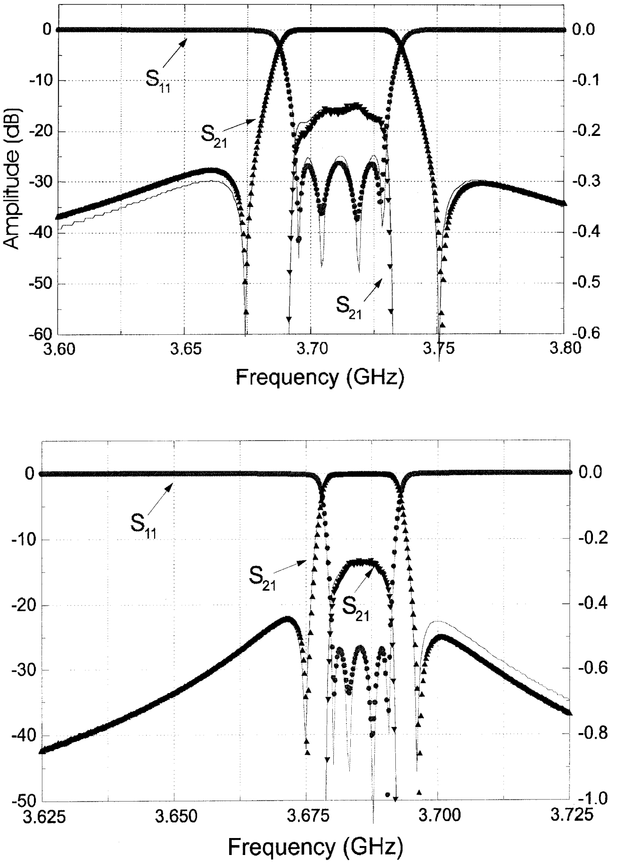


Fig. 1. Measured S-parameter of a C-band quasielliptic four-pole filter for two different values of the bandwidth BW: (a) BW = 36 MHz or 1% and (b) BW = 10 MHz or 0.3%. All measurements have been performed at room temperature.

Our filter approach has been used to develop space qualified output multiplexer (OMUX) filters for C-band communication satellites. Recently, a fully operational three channel OMUX has been demonstrated.[3] Currently, we are developing L-band quasielliptic 8 and 12-pole filters for UMTS base stations based on our novel concept.

3. Cryogenic whispering gallery mode resonators for stable microwave oscillators

Whispering-gallery modes are modes with high azimuthal mode number which can exist if boundary conditions with circular symmetry are present. The name originates from sound waves being totally reflected from the cylindrically shaped wall inside the so-called "whispering gallery" of St Paul's cathedral in London. For electromagnetic waves total reflection occurring at the transition from a medium with high to a medium with low refractive index can be utilised to create whispering-gallery mode resonators with unloaded quality almost entirely determined by dielectric losses, i.e. the geometric factor G in Eq. (1) approaches infinity.

Whispering-gallery mode resonators based on sapphire cylinders provide the highest quality factors above an operation temperature of 10 K. The loss tangent of sapphire varies from about 10^{-5} at room temperature down to below 10^{-7} at liquid nitrogen temperatures ($f = 10$ GHz).[8] Such high quality factors have a strong potential to be used for microwave oscillators with phase noise below that of microwave sources being phased-locked to quartz oscillators.

We have developed an all-cyrogenic K-band oscillator for $f = 23$ GHz with a three-step mechanical and electrical frequency tuning (Fig. 2a). The parts of this hybrid oscillator are as follows (for more details see Ref. 4):

- A whispering gallery mode resonator with a mechanical tuning range of 60 MHz and a piezo-mechanical fine tuning range of 50 kHz. The unloaded quality factor was found to be $5 \cdot 10^6$ at 77 K over the entire tuning range.
- A cryogenic two-stage HEMT amplifier including a semiconductor varactor phase shifter and a 10 dB output coupler.
- A one or two pole narrow bandpass filter which guarantees that our feedback oscillator cannot be locked to any spurious mode.

Fig. 2b shows the measured phase noise. The amplifier phase noise (full squares) was found to be nearly independent of temperature between room temperature and 77 K. The measured values of amplifier phase noise indicate $1/f$ behaviour with an absolute value of -132 dBc/Hz at 1 kHz offset frequency. According to comparative measurements with commercial broad band amplifiers at the same frequency, this value is quite low.

The oscillator phase noise calculated from the amplifier phase noise according to the Leeson model [7] is −120 dBc/Hz at 1 kHz offset frequency (full circles). This is well below that of quartz reference based microwave oscillators at the same frequency. However, the oscillator phase noise measured using a microwave downconverter and a quartz reference is about 10 dB above (at 1 kHz offset) the calculated values. This discrepancy is due to the noise floor of the downconverter. Comparative measurements of two identical oscillators are in progress.

Our results indicate that phase noise values below that of quartz sources can be achieved by this technique. Such oscillators are considered to be applicable for high bit links in satellite communication and for high sensitive Doppler radar systems.

One drawback of sapphire as material for dielectric resonators is the relatively large temperature coefficient of the resonance frequency of 60 ppm/K at 77 K. In order to improve the frequency variation with temperature significantly we have developed a composite rutile/sapphire resonator. Utilising the opposite sign of $d\varepsilon_r/dT$ of rutile[9] and sapphire one can generate a turning point in the temperature dependence of the resonance frequency f, i.e. a temperature where $df/dT = 0$.[10] The temperature of the turning point is defined by selecting the volume fraction of rutile. Our design of such a resonator is shown in Fig. 3a, details are given in Ref. 5.

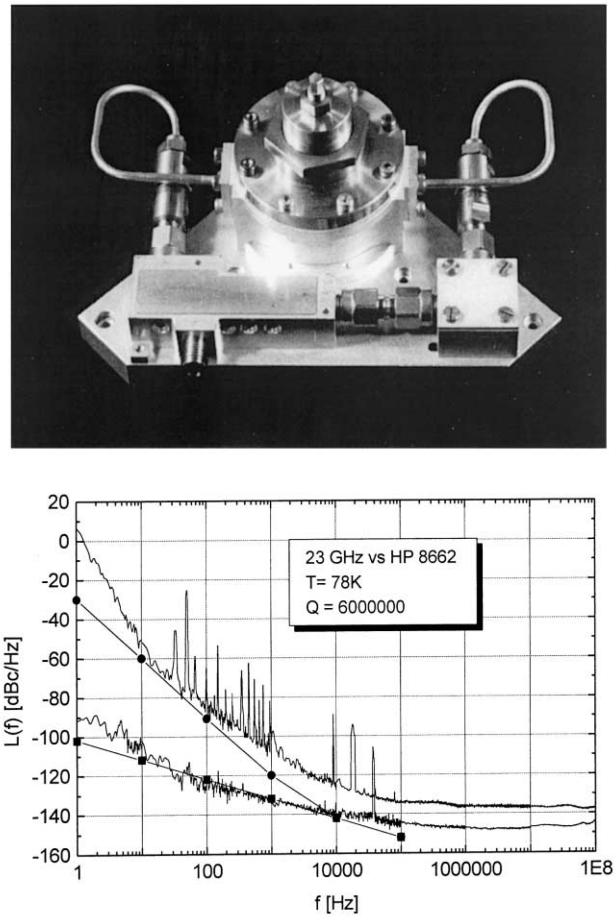


Fig. 2. Photograph of (a) a cryogenic 23 GHz oscillator consisting of a whispering-gallery mode resonator (large circular metal housing), a two-stage HEMT-amplifier (rectangular housing) and a mode selection bandpass filter (square housing); (b) shows the measured phase noise (explanation in text).

Fig. 3b shows the experimentally determined frequency vs. temperature for temperatures around the turning point at 78 K. The value of the quadratic slope of the fit curve at the turning point, $1/f\ \partial^2 f/\partial T^2$, was determined to be only −0.9 ppm/K^2, i.e. a temperature stability of one millikelvin would correspond to a relative frequency change of only $-4.2\cdot 10^{-13}$. The unloaded quality factor was measured to be $4\cdot 10^6$ corresponding to the intrinsic losses of sapphire and rutile.[9] Therefore, such composite resonators have a strong potential to be employed as microwave frequency standards with very low phase noise in the future.

4. Whispering-gallery type modes originating from Bragg reflection by photonic crystals

To date, whispering-gallery mode resonators based on total reflection at a dielectric interface represents the

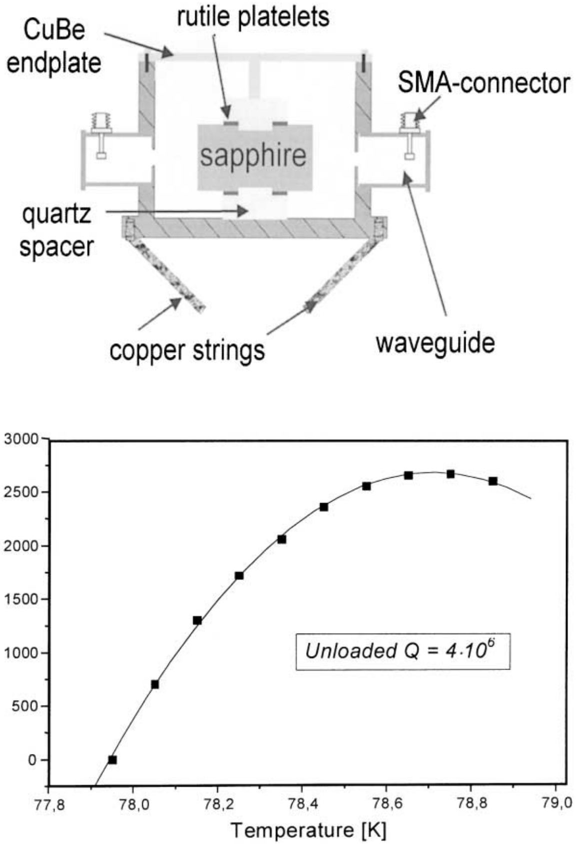
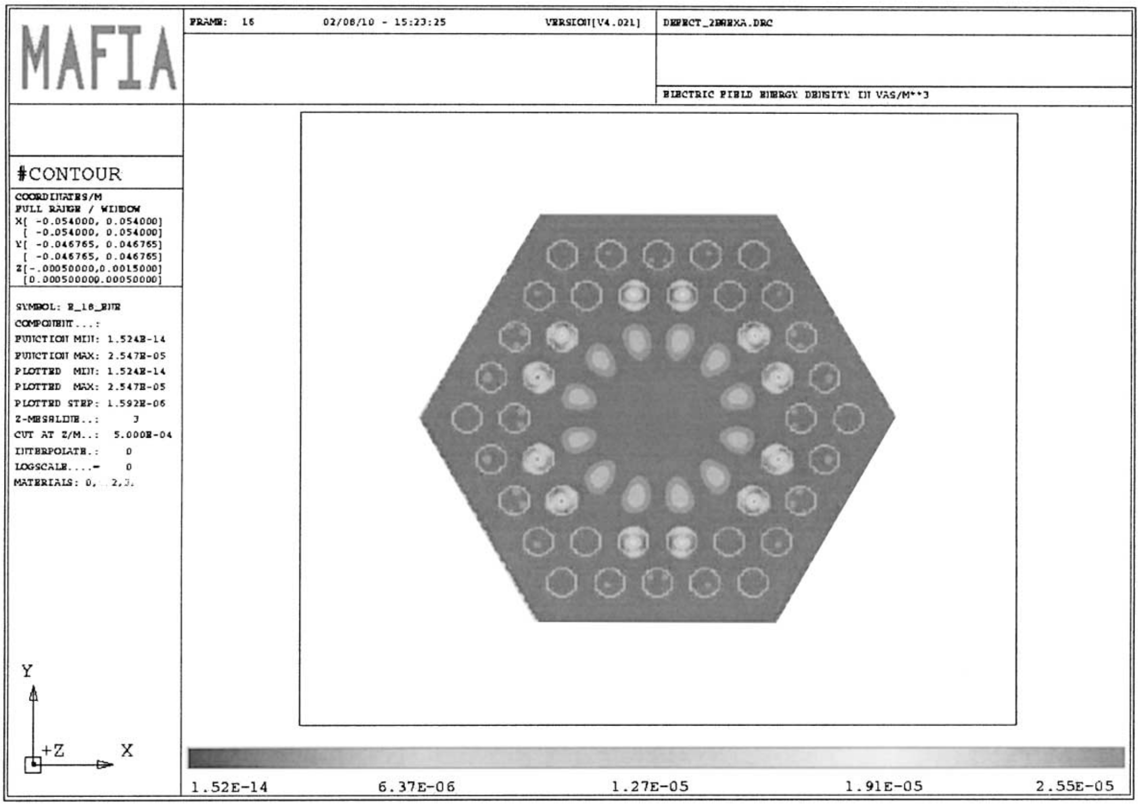


Fig. 3. X-band rutile/sapphire composite whispering-gallery mode resonator with (a) waveguide coupling and (b) measured resonance frequency (f–9.96310 GHz) versus temperature.



```
FRAME:  16          02/08/10 - 15:23:25          VERSION[V4.021]
DEFECT_2BHEXA.DRC
ELECTRIC FIELD ENERGY DENSITY IN VAS/M**3

#CONTOUR
COORDINATES/M
FULL RANGE / WINDOW
X[ -0.054000, 0.054000]
 [ -0.054000, 0.054000]
Y[ -0.046765, 0.046765]
 [ -0.046765, 0.046765]
Z[-.00050000,0.0015000]
 [0.000500000.00050000]

SYMBOL: E_18_ENE
COMPONENT...:
FUNCTION MIN: 1.524E-14
FUNCTION MAX: 2.547E-05
PLOTTED  MIN: 1.524E-14
PLOTTED  MAX: 2.547E-05
PLOTTED STEP: 1.592E-06
Z-MESHLINE..:      3
CUT AT Z/M..:  5.000E-04
INTERPOLATE.:     0
LOGSCALE....-     0
MATERIALS: 0,  2,3.
```

Fig. 4. Calculated distribution of electric field energy of a quasi two-dimensional whispering-gallery type resonance formed by Bragg reflection from a photonic bandgap structure.

optimum solution with respect to low loss contribution of the metallic shielding cavity. Since dielectric losses determined by the interaction of electromagnetic wave with the phonon system are of intrinsic nature, it may be difficult—if not impossible—to find any material with lower $\tan\delta$ values than sapphire. Therefore, according to Eq. (1) the only way to improve the Q value of a dielectric resonator at room temperature is the reduction of the filling factor κ, which is close to unity for whispering-gallery mode resonators. This is not an easy task, because on the one hand a high permittivity dielectric material is essential to reduce the metallic wall losses, on the other hand it tends to attract the electromagnetic field and thus leads to a significant contribution to electromagnetic field energy stored in the dielectric material.

Our novel approach to overcome this problem relies on the utilisation of Bragg reflection by photonic crystals rather than total reflection to create a whispering-gallery type resonance. Fig. 4 shows a first result of an electromagnetic field simulation using the computer code "MAFIA".[6] The quasi-two dimensional structure consists of a hexagonal lattice of alumina rods arranged inside a metallic shielding cavity with a hexagon shaped empty region in the centre. The photonic crystals were designed to provide a suitable bandgap around the resonant frequency of the empty hexagon. Fig. 4 shows the distribution of electric field energy indicating the whispering-gallery type symmetry with azimuthal mode number $n=6$. It is remarkable that only two rows of alumina rods are sufficient to suppress the field at the metal walls to a significant amount. The filling factor of all dielectric rods κ was found to be 0.558. Fig. 4 indicates that whispering-gallery type modes created by Bragg reflection could be a challenging alternative to increase the Q factors of dielectric resonators beyond the limit determined by $1/\tan\delta$.

5. Conclusion

Novel dielectric resonator structures offer a challenging potential to utilise progress in the development of low loss microwave ceramics. Resonator geometries optimised with respect to a low loss contribution of the metallic surrounding, low loss contribution of the dielectric resonator, high temperature stability plus the subsequent development of single- and multi-resonator devices have been demonstrated and may play an important role for future microwave communication systems.

Acknowledgements

The work on the filters and the all-cryogenic low phase noise oscillator has been financially supported by

Robert Bosch GmbH in the framework of a project funded by the German Ministry of Research and Education. Additional funding has been provided by the European Commission in the framework of EU-projects "DiHiMiCo" and "FOAMS".

References

1. Schornstein, S., Ghosh, I. S. and Klein, N., High-temperature superconducting shielded high-power dielectric dual-mode filter for applications in satellite communications. *Conference Digest of the IEEE—MTT-S Int. Microwave Symp.*, 1998, **98**, 1319–1322.
2. Klein, N., Schornstein, S., Ghosh, I. S., Schemion, D., Winter, M. and Zuccaro, C., High-*Q* dielectric resonator devices at cryogenic temperatures. *IEEE Transactions on Applied Superconductivity*, 1999, **9**, 3573–3576.
3. Klauda, M., Kässer, T., Mayer, B., Neumann, C., Schnell, F., Aminov, B., Baumfalk, A., Chaloupka, H., Kolesov, S., Piel, H., Klein, N., Schornstein, S., Bareiss, M., Superconductors and cryogenics for future communication systems. *IEEE Transactions on Microwave Theory and Techniques*, 2000, **48**, 1227–1239.
4. Klein, N., Vitusevich, S., Winter, M. and Yi, H. R., Novel high Q dielectric resonator devices for satellite communication. In *Proceedings of the ECSC 5*, 1999, Toulouse.
5. Winter, M., Klein, N., Hao, L. and Gallop, J. C., Cryogenic composite whispering-gallery resonators for low-phase noise frequency standards. *Presentation at the 2000 IEEE Frequency Control Symposium*, 2000 Kansas City. To be published in the Proceedings.
6. Schmidt, D. and Weiland, T., Status and future of the 3d mafia group of codes. *IEEE Trans. Magn.*, 1992, **28**, 1793–1796.
7. Leeson, D. B., A simple model of feedback oscillator noise spectrum. In *Proc. IEEE*, 1966, **54**, 329–330.
8. Braginsky, V. B., Ilchenko, V. S. and Bagdassarov, K. S., Experimental observation of fundamental microwave absorption in high quality dielectric crystals. *Phys. Lett. A*, 1987, **120**, 300–305.
9. Klein, N., Zuccaro, C., Dähne, U., Schulz, H., Tellmann, N., Kutzner, R., Zaitsev, A. G. and Wördenweber, R., Dielectric properties of rutile and its use in high temperature superconducting resonators. *Journal of Applied Physics*, 1995, **78**, 6683–6686.
10. Klein, N., Scholen, A., Tellmann, N., Zuccaro, C. and Urban, K. W., Properties and applications of HTS-shielded dielectric resonators: a state-of-the-art report. *IEEE Transactions on Microwave Theory and Techniques*, 1996, **44**, 1369–1373.