ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB035

A CRYOGENIC DIELECTRIC PULSE COMPRESSOR

S. V. Kuzikov†, Euclid Techlabs LLC, Bolingbrook, IL

Abstract

Efforts aimed at developing klystron parameters have made significant progress in recent years [1]. However, the ultimate parameter list of connected pulse compressors (PCs) has been given insufficient attention. We propose to develop a new high efficiency, high power gain pulse compressor based on the use of a dielectric storage resonator (100% dielectric filling factor) that is operated at a cryogenic temperature (77 K). It is well known that, at cryogenic temperatures, a copper cavity can gain a much higher Q factor. However, at cryogenic temperatures, the RF loss tangent of some dielectric materials also decreases substantially (tanδ~10^{-9} for Sapphire at 10 K). This inspires our effort to develop dielectric resonators for PCs with an intrinsic quality factor, Q_0, that is several orders of magnitude higher than the Q_0 for all metallic resonators at room temperature, and at least twice as high as for cryogenic copper cavities. In addition, the dielectric storage cavity can make the PC system more compact and lower their cost. We anticipate improving the parameters of the well-known SLED-II PCs. We consider both a passive PC (switched with a fast change of the klystron's phase) as well as an active PC (which requires a fast RF switch).

CRYOGENIC HIGH-Q RESONATORS

Two of the best-known pulse compression systems used for room temperature RF accelerators are the SLED and SLED-II PCs (Fig. 1). Both of these use hollow copper storage resonators (SLED) or delay lines (SLED-II) that accumulate RF energy from an incident RF pulse [2, 3]. The resonators work in low-loss TE_{01} or higher order axisymmetric modes. Unlike the SLED PC that has a decaying output pulse, the SLED-II was designed to provide a flattop output RF pulse that is the best shape for feeding accelerating structures. The compressed pulse arises when the phase of the incident RF pulse is sharply changed by 180°. These PCs are often called passive PCs because the properties of the resonators or delay lines are never changed. A pair of resonators or delay lines are fed by a -3-dB hybrid coupler that protects the RF source from the undesirable reflection that occurs during the transient process of RF power accumulation. The SLED PC can provide up to 9× power gain, P_g (ratio of the output pulse power to the incident pulse power). For maximum power gain, the efficiency (η), defined as the ratio of the energy in the output pulse to the incident energy, is very low. Typically, SLED works with power gain ~4, in which case the compression ratio, C_r (ratio of incident pulse length to the length of the compressed pulse) equals 6. The efficiency in this case can be as high as 67% [2].

† s.kuzikov@euclidtechlabs.com

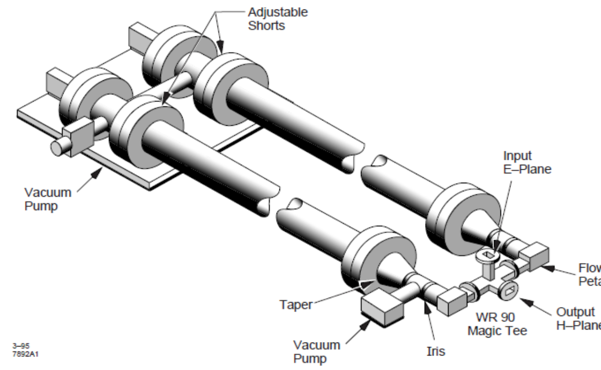

Figure 1: SLED-II layout. Tested with 12.065-cm diameter waveguide, 22.5-m in length (150-ns round-trip RF transit time) [2].

The obtainable parameters for the compression, power gain, and efficiency depend on the internal losses of the PC. Obviously, the lower the losses, the higher these parameters will be. To reduce the losses in the storage resonators, one can cool them down. Another idea is to substitute low-loss dielectric waveguides for the copper waveguides that are typically employed. Additional loss reduction can be obtained using dielectric materials at cryogenic temperature, taking advantage of the fact that, below some threshold temperature, the losses in all types of dielectrics go down as the temperature is decreased. Table 1 summarizes the properties of two of the most appealing dielectric materials, Magnesia and Sapphire, in X-band at different temperatures. The data for Magnesia are taken from Refs. [4, 5]. Sapphire, a particular type of Corundum crystal (another one is Ruby), was well characterized in Refs. [6, 7].

Table 1: Properties of Materials at Cryogenic Temperatures in X-Band

Material	300 K	77 K	45 K
Magnesia	ε=9.64 tanδ=$7\cdot10^{-7}$	ε=9.64 tanδ=$1\cdot10^{-7}$	-
Sapphire	ε=11.6 tanδ=$1\cdot10^{-5}$	ε=11.36 tanδ=$1\cdot10^{-8}$-$1\cdot10^{-7}$	ε=11.34 tanδ=$5\cdot10^{-9}$-$1\cdot10^{-7}$
Quartz	ε=4.4-4.6 tanδ=$1\cdot10^{-4}$	ε=4.4-4.6 tanδ=$2\cdot10^{-6}$-$1\cdot10^{-5}$	ε=4.4-4.6 tanδ=$2\cdot10^{-6}$-$1\cdot10^{-5}$

Let us consider a rod packed in a quartz envelope (see Fig. 2). Good guiding properties come from the effect of total internal reflection (TIR). A wave propagating in a dielectric rod (made of Magnesia or Sapphire) with a high refractive index does not leak into a medium, like vacuum or quartz, which has a low refractive index. Remarkably, this configuration does not contain any dielectric-vacuum interfaces at a field level that can cause multipactor discharge.

32nd Linear Accelerator Conference (LINAC2024),Chicago, IL, USA JACoW Publishing
ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB035

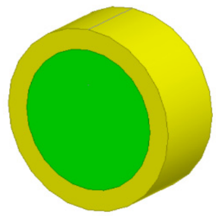

Figure 2: Waveguide based on quartz-clad dielectric rod.

To calculate the losses in dielectric waveguides, we have used HFSS to simulate a TE_{01} standing-wave resonator with perfectly conducting ends. In Fig. 3, one can see the resonator with a quartz-clad sapphire rod. One can see that the fields at the quartz-vacuum boundary are more than 10^3 times less that the field maximum in the main body of the rod. The Q-factor of the described resonator mode $TE_{0,1,7}$ mode trapped by TIR has the highest Q-factor, at least 10 times higher among all others.

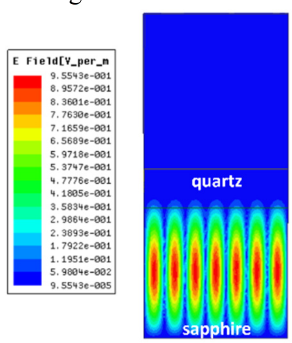

Figure 3: E-field distribution of the $TE_{0,1,7}$ mode in a sapphire resonator enclosed by quartz tube.

PASSIVE SLED-II PULSE COMPRESSOR

Let us consider the passive 11.424-GHz SLED-II PC with dielectric waveguides marked in green and yellow (Fig. 4). The grey colour designates vacuum metallic waveguides. At the coupler, only the TE_{01} mode among all other axisymmetric modes can propagate. Let us assume that we need a ~100-ns flattop compressed pulse, so that for a pure copper waveguide PC let us choose the lengths of every two delay waveguides to be 17.5 m. For the dielectric waveguide, the length must be $1/\sqrt{\varepsilon}$ less due to a smaller group velocity. Losses in a ∅54-mm sapphire waveguide with 8 mm quartz envelop and in a Magnesia waveguide with the same diameter and envelop are plotted in Fig. 5 in comparison with losses in a copper waveguide of the same diameter (54 mm). The quartz tube envelop was as thick as 8 mm. One can see from Fig. 5 that dielectric waveguides look much better than copper waveguide from the viewpoint of the total losses.

Knowing the round-trip losses in the delay waveguides, we could then simulate the pulse compression parameters. The results of the simulations are shown in Fig. 6. At 77K, the SLED-II configuration based on Sapphire-Quartz delay lines can provide a power gain as high as about 5.2 (Cr=8 at η=64%).

Note that some dielectric waveguide configurations for pulse compression have been considered at SLAC [8].

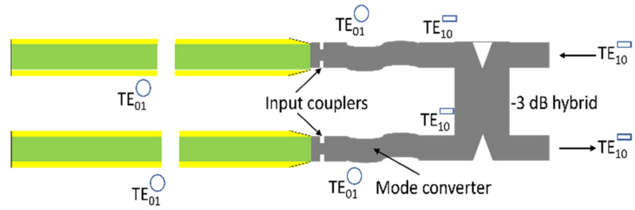

Figure 4: Sketch of passive SLED-II pulse compressor based on the use of dielectric waveguides enclosed by quartz tubes.

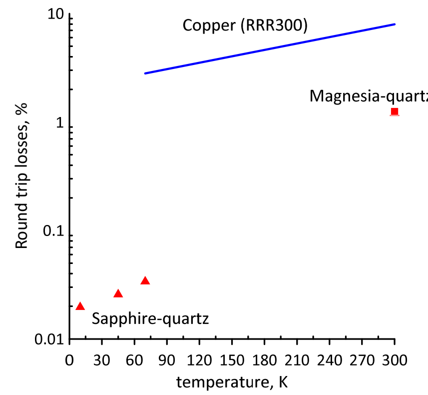

Figure 5: Round trip losses in TE_{01} SLED-II delay waveguide for Sapphire-quartz, Magnesia-quartz and pure copper materials vs temperature.

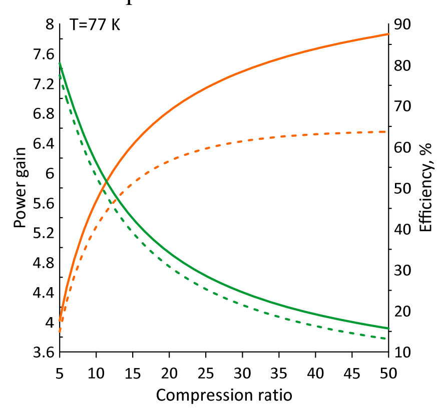

Figure 6: Power gain (orange) and efficiency (green) for a passive SLED-II compressor made of sapphire with a quartz envelop (solid curves) and made of copper (dashed curves) at 77 K.

ACTIVE SLED-II PULSE COMPRESSOR

Let us consider a so-called active PC (Fig. 7). Active PCs are appealing due to the higher power gain that can be achieved. The active PC exploits fast RF switches in each of the two channels. These switches allow one to modulate the external Q factor of the delay line resonators. The proposed design assumes that the delay waveguides act as cavities to accumulate RF energy in the TE_{02} mode. In the energy storage regime, there is a small TE_{01}-TE_{02} conversion due to the switch. In the regime of power extraction, the TE_{01}-TE_{02} conversion sharply increases due to photoinduced switching, so that the power stored in the delay line can be extracted in a single round-trip transit through the

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB035

delay line. The concept of a TE_{01}-TE_{02} PC was published in [9].

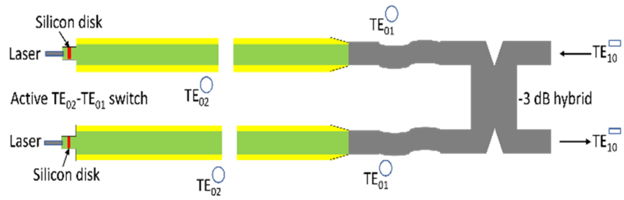

Figure 7: Sketch of an active SLED-II pulse compressor based on a dielectric waveguide with quartz envelop.

The RF switch sketches for the mentioned accumulation and extraction regimes are shown in Fig. 8 and Fig. 9, respectively. The semiconductor disk in the single-mode part of the switch can be irradiated with a laser that induces photoconductivity if the laser photon energy exceeds the bandgap energy of the silicon (1.12 eV). If the concentration of free carriers becomes high enough, the silicon disk starts playing the role of a metal, thus changing the conversion fraction of the TE_{02} into the TE_{01} mode. The experiments with silicon switched with an 800-nm laser and irradiated by a 30-GHz wave have shown that the silicon disk starts to reflect more than 90% of the RF power when the laser energy reaches the level of 5 mJ/cm^2 [10].

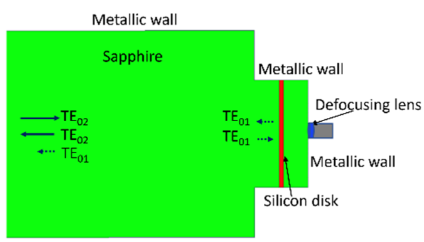

Figure 8: TE_{01}-TE_{02} mode conversion switch in regime of power accumulation in the storage resonator.

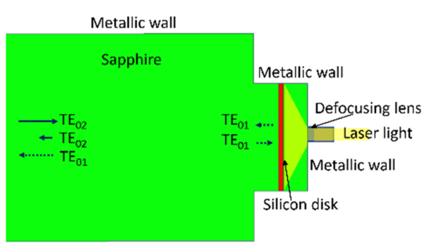

Figure 9: RF switch in regime of power extraction.

Figure 10 illustrates a simulation of the RF switch with an inserted 0.5-mm-thick silicon disk. In the regime of power accumulation the silicon disk is nearly transparent for the TE_{01} mode. When irradiated by the laser, the silicon disk begins to reflect the incoming wave (Fig. 11), with the result that the conversion of the TE_{02} mode into TE_{01} reaches the -0.5 dB.

Let us analyze parameters of the compression for the active PC with the same delay line sizes that were considered in the Section devoted to the passive PC One can see at Fig. 12 that the sapphire-quartz delay waveguides at 77 K make possible more than 80% efficiency for as high power gain as a factor of 40.

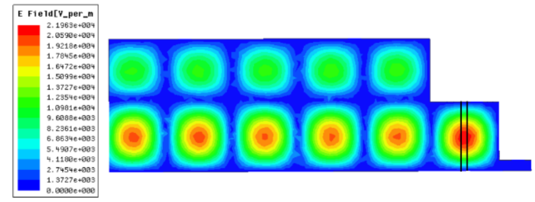

Figure 10: E-field distribution in the energy accumulation regime.

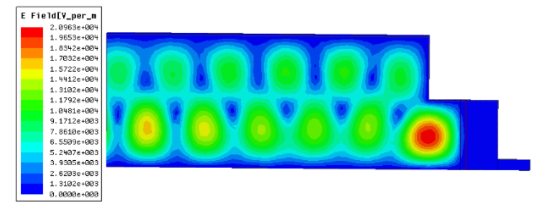

Figure 11: E-field distribution in the energy extraction regime.

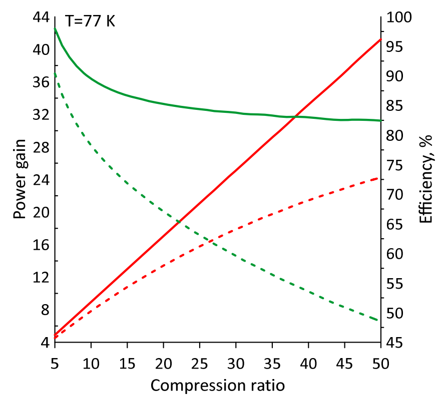

Figure 12: Power gain (orange) and efficiency (green) for active SLED-II compressor made of quartz-clad sapphire rods (solid curves) and made of copper (dashed curves) at 77 K.

CONCLUSION

The best results for power gain and efficiency could be obtained using the sapphire classic SLED-II waveguides at 77 K. The passive SLED-II PC at this temperature is appealing due to a doubling of the efficiency in comparison with classic SLED-II for a power gain 5.2. The active PC might provide an even higher power gain, as high as several factors of ten, at an efficiency as high as 80%.

REFERENCES

[1] T. L. Barklow *et al.*, “An Advanced NCRF Linac Concept for a High Energy e^+e^- Linear Collider,” 2018. doi:10.48550/arXiv.1807.10195

[2] P. B. Wilson *et al.*, “SLED-II: A new method of rf pulse compression,” in *Proc. LINAC’90*, Albuquerque, NM, Sep. 1990, pp. 204-206.

[3] S. G. Tantawi, R. J. Loewen, C. D. Nantista, and A. E. Vlieks, “The generation of 400-MW RF pulses at X-band using resonant delay lines,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 12, pp. 2539–2546, 1999. doi:10.1109/22.809004

[4] J. Mazierska, D. Ledenyov, M. V. Jacob, and J. Krupka, “Precise microwave characterization of MgO substrates for

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB035

HTS circuits with superconducting post dielectric resonator," *Supercond. Sci. Technol.*, vol. 18, no. 1, pp. 18–23, Nov. 2004. doi:10.1088/0953-2048/18/1/004

[5] D. Satoh, M. Yoshida, and N. Hayashizaki, "Fabrication and cold test of dielectric assist accelerating structure," *Phys. Rev. Accel. Beams*, vol. 20, no. 9, Sep. 2017. doi:10.1103/physrevaccelbeams.20.091302

[6] V. B. Braginsky, V. S. Ilchenko, and Kh. S. Bagdassarov, "Experimental observation of fundamental microwave absorption in high-quality dielectric crystals," *Mod. Phys. Lett. A*, vol. 120, no. 6, pp. 300–305, Mar. 1987. doi:10.1016/0375-9601(87)90676-1

[7] J. Krupka, K. Derzakowski, M. Tobar, J. Hartnett, and R. G. Geyer, "Complex permittivity of some ultralow loss dielectric crystals at cryogenic temperatures," *Meas. Sci. Technol.*, vol. 10, no. 5, pp. 387–392, Jan. 1999. doi:10.1088/0957-0233/10/5/308

[8] S. G. Tantawi, R. D. Ruth, A. E. Vlieks, and M. Zolotorev, "Active high-power RF pulse compression using optically switched resonant delay lines," *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 8, pp. 1486–1492, 1997. doi:10.1109/22.618460

[9] A. L. Vikharev, A. M. Gorbachev, O. A. Ivanov, V. A. Isaev, S. V. Kuzikov, and M. A. Lobaev, "A plasma switch based on TE02 → TE01 round waveguide mode conversion for high-power X-band microwave compressors," *Tech. Phys. Lett.*, vol. 33, no. 9, pp. 785–787, Sep. 2007. doi:10.1134/s1063785007090210

[10] A. A. Vikharev *et al.*, "Fast quasi-optical phase shifter based on the effect of induced photo conductivity in silicon," *Radiophys. Quantum Electron.*, vol. 50, no. 10–11, pp. 786–793, Oct. 2007. doi:10.1007/s11141-007-0069-x