Radiation Hardness of High-Q Silicon Nitride Microresonators for Space Compatible Integrated Optics

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Abstract
Integrated optics has distinct advantages for applications in space because it integrates many elements onto a monolithic, robust chip. As the development of different building blocks for integrated optics advances, it is of interest to answer the important question of their resistance with respect to ionizing radiation. Here we investigate effects of proton radiation on high-Q ($Q(10^6)$) silicon nitride microresonators formed by a waveguide ring. We show that the irradiation with high-energy protons has no lasting effect on the linear optical losses of the microresonators.

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Optics has been an important part of space systems even since the early years of space exploration. While imaging optics were part of some of the first instruments in space, the field of optics keeps expanding and in particular the field of integrated optics shows great potential for multiple applications with its distinct advantages of small size, robustness against vibrations and high degree of integration. The effect of ionizing radiation in space has been tested in many studies for discrete optics [1–5] as well as fiber optics [1, 6–9]. From these studies it is well known that radiation can change the optical properties of glasses which can lead to increased losses. However, this important aspect of space compatibility has not been investigated extensively for integrated optics [10, 11]. Here we study the radiation hardness of waveguide microresonators made from silicon nitride (SiN) [12, 13] with quality factors (Q-factors) around $10^6$. These microresonators can find applications as optical frequency comb generators and optical filters [14–16]. The optical frequency combs generated inside the resonators have frequency spacings of around 10 GHz to 1 THz and span several hundred nm [14, 15, 17]. Frequency combs can be crucial parts of future space missions and applications. Examples for missions in the field of fundamental physics that would benefit of such a device are the missions “Space Optical Clock” (SOC) [18] on the ISS, the “Einstein Gravity Explorer” (EGE) [19], and the “Space Time Explorer and Quantum Test of the Equivalence Principle” (STE-QUEST) [5, 20]. In the first and second mission, a frequency comb is required to convert the laser radiation of an optical clock into microwave radiation that is transmitted to ground where its frequency is measured. In the STE-QUEST mission, a microwave-optical local oscillator has been proposed as part of a microwave cold Cs atomic clock, which provides, again via conversion by a frequency comb, an ultrastable 9 GHz microwave for interrogation of the atomic clock.

The generation of microresonator frequency combs relies on the Kerr nonlinearity of the silicon nitride resonator. The effect of the nonlinearity is greatly enhanced by the high Q-factor of the resonator, the threshold for the parametric oscillation scales as $1/Q^2$ [15, 21]. Therefore the Q-factor of a microresonator is an important parameter for these applications. The Q-factor is limited by the optical losses of the waveguide ring resonator which are caused by absorption as well as scattering. Therefore, a change in Q-factor directly relates to changed losses of the waveguide.

One of the key requirements for space equipment is radiation resistance. Satellites on orbits that cross the Van Allen belt are exposed strongly to electron and proton radiation. Components of instruments that are to be flown on such orbits must therefore be tested beforehand with respect to their radiation resistance. The mentioned missions EGE and STE-QUEST rely on such orbits. In this work, we perform a first investigation of the influence of proton radiation on the Q-factor as a key property of microresonators.

The microresonators under test are waveguide ring resonators. A SiN waveguide with dimensions $0.8 \mu m$ by $2 \mu m$ and with a refractive index of 1.98 confines the light and is embedded into a silicon dioxide (SiO$_2$) cladding with refractive index of approximately 1.45 (Fig. 1(a)). From simulations we know that at 1550 nm about 80% of the power travels inside the SiN and 20% in the SiO$_2$. To fabricate the ring microresonators, standard p-doped (boron doping, resistivity of 10 to 20 $\Omega$cm) 100 nm silicon wafers are oxidized in a thermal wet oxidation process in order to grow a film of 4 $\mu m$ SiO$_2$. On top, 800 nm of silicon nitride (Si$_3$N$_4$) is deposited as nearly stoichiometric high-stress thin film via low pressure chemical vapor deposition (LPCVD). After patterning the silicon nitride using electron-beam lithography and reactive-ion etching the 3 $\mu m$ thick SiO$_2$ top cladding is deposited as low-temperature CVD oxide followed by a thermal anneal. In a last step chips of 5 mm by 5.5 mm are separated. One chip comprises multiple resonators. Each resonator is evanescently coupled to one separate bus waveguide which allows to couple light in and out of the resonator...
As outlined above, the Q-factor is one of the most important properties of the resonator and the most likely to undergo significant changes under irradiation. Therefore we selected two chips from different wafers and two resonators on each chip and characterized their Q-factors. The quality factor was measured by determining the loaded linewidth ($\kappa/2\pi$ in Hz) of multiple resonances between 1520 and 1580 nm of the respective resonator. The Q-factor relates to the linewidth as $Q = \omega/\kappa$ where $\omega$ is the optical resonance frequency. The linewidths of the resonances were measured by scanning an external cavity diode laser with a linewidth of approximately 300 kHz over the resonances. The polarization does not have an effect on the linewidths of the resonance, however, the contrast and the lineshape depend on the polarization. Therefore the polarization of the laser was optimized by hand to yield minimal transmission through the bus waveguide with the laser on resonance and a lineshape with as little distortion from a Lorentzian shape as possible. The laser scan was calibrated in frequency using a fiber frequency comb which provides a frequency calibration marker approximately every 60 MHz with 1 MHz precision. In most cases a good fit of the transmission curve could be obtained with a simple Lorentzian lineshape function. For resonances that showed a splitting due to the coupling of the co- and counter-propagating modes, we fitted a model that takes this splitting into account. The average linewidths of the four measured resonators (resonator I to IV) varied from 250 MHz to 440 MHz.

After the initial characterization the chips were sent for the irradiation. After the irradiation was performed as described below the chips were shipped back and the linewidths were measured again to check for changes. For each resonance that was measured before the irradiation the polarization-dependent shape of the resonance was again optimized to yield a minimal transmission on resonance (for resonances of Chip 1 with resonators I and II, dark blue and green data in Fig. 3 respectively) or to obtain a best possible match with the shape of the resonance measured before the irradiation (Chip 2 with resonator III and IV, red and light blue data). Due to the shipments and preparation for the irradiation as well as the extensive manual measurements the whole procedure stretched over 12 weeks. Therefore, potentially short lasting irradiation effects as they have been reported in fibers are not well reflected in our measurements.

Proton irradiation of the sample can have multiple effects which are caused by the interaction with the material. As the critical part of our chips is only around 8 $\mu$m thick, most of the protons with energies above approximately 1 MeV pass through this part. The average energy deposited in the sample depends on the energy loss function as it can be calculated for different materials. In Fig. 1 the results of simulations for the two relevant materials for this work, silicon nitride and silicon dioxide, are shown.

The starting point of the irradiation study is the result of modeling the proton spectrum experienced by a spacecraft on a specific orbit. We assume here the highly elliptic orbit proposed for the STE-QUEST mission. It is characterized by a 16-hour period, a perigee altitude (above ground) varying between 800 and 2400 km during the course of the 5-year long mission, and a constant apogee altitude of approximately 51 000 km. The time-averaged spectral (i.e. energy-dependent or differential) fluence of the proton radiation, and the corresponding time-averaged and energy-integrated (integral) fluence of the protons, calculated in Ref. [29], are shown in Fig. 2 (red line). The energy-integrated fluence at energy $E$ is defined as the integral of the differential fluence from infinite energy down to $E$. Note that the two quantities have a similar energy dependence for this orbit. The quantities refer to the radiation arriving on the satellite.

When one considers the radiation reaching a particu-
lar component in an instrument in the satellite, one must consider that this component is shielded by other components of the satellite (satellite structure, solar panels, housing of the instrument, additional specific shielding layers) in a way that depends on the details of the spacecraft and the instruments. The amount of shielding can be different in different directions with respect to the spacecraft axes. The details are usually not known with certainty a priori, since they are worked out during the detailed planning of the mission, which only occurs after selection of the mission by the space agency.

We therefore first consider as an example a shielding having an equivalent thickness of 2 mm aluminum (blue lines in Fig. 2). Such a thickness is likely to be present even without installing additional shielding. We see that the result is an extremely strong reduction of the fluences at energies below 10 MeV. The modified fluence was computed using the software MULASSIS [30, 31]. In this program, one layer of aluminum shielding is considered and the modification of an input spectrum is then calculated, yielding an output spectrum.

We can assume the existence of 10 mm aluminum shielding, which would arise from structural shielding plus possibly an additional custom housing enclosing the microresonator. The resulting fluences reaching the component are shown in green in the plots. The increased shielding thickness results in an additional factor 10 reduction in the fluences below 10 MeV. The fluences then have values that are well accessible by an irradiation run produced by a proton accelerator. The task is then to devise an irradiation protocol that models the predicted, shielded space proton spectrum reasonably well.

The proton irradiation test was carried out at the Paul-Scherrer-Institut (PSI) in Villigen, Switzerland. The maximum energy available at this facility is 99.7 MeV. This sets an upper limit for the energy of the space proton spectrum that can be reproduced. Considering that protons with energy lower than 20 MeV would be effectively stopped (i.e. absorbed) by a 2 mm aluminum shield, the samples were irradiated with protons with energies on the order of and higher than 20 MeV. The samples were irradiated with 4 energies, 18.3, 30.7, 61.6, and 99.7 MeV. Except for the last one, these energies are the mean energies after degradation of the proton beam by a copper plate ("degrader") of thickness 12.5, 11.5, and 7.5 mm, respectively, inserted into the proton beam. The fluences of the proton beam (upstream of the respective degrader) were set to $6.000 \times 10^{10}$, $4.003 \times 10^{10}$, $1.416 \times 10^{10}$, and $1.516 \times 10^{10}$ protons/cm², respectively.

The integral and differential fluence of the implemented irradiation of the samples are shown in purple in Fig. 2. They are the sum of four individual fluences, each of which corresponds to the simulated fluence of a 99.7 MeV proton beam degraded by the respective copper degrader (if any).

In more detail, the differential fluence reproduces well the low-energy region ($E < 10$ MeV) of the 10 mm shielded space spectrum. In the range 18 to 100 MeV the spectrum consists of four peaks, rather than a continuous spectrum, which are remainders of the energies of the proton beam. We believe that this is of no consequence; in other words, the potential damage done to the sample will likely not depend on the details of the energy spectrum in the range 18 – 100 MeV. The overall situation is that the implemented integral fluence exceeds both the 10 mm-shielded as well as the 2 mm-shielded integral space fluence at all energies $E < 100$ MeV. Therefore, the implemented fluence is a conservative choice for a 5-year STE-QUEST mission duration having a 10 mm aluminum shielding. In addition, the integral fluence down to $E = 18$ MeV is a factor 2 above the unshielded STE-QUEST space spectrum (red line in the figure), also indicating the conservative nature of our test irradiation protocol.

In Fig. 3 the mean linewidths of pre and post radiated samples $(\kappa_{\text{after}} + \kappa_{\text{before}})/4\pi$ as well as the difference in linewidths $(\Delta\kappa/2\pi = \kappa_{\text{after}}/2\pi - \kappa_{\text{before}}/2\pi)$ between the measurements are shown. To determine the possible effects of the radiation on the Q-factor $\Delta\kappa$ is plotted in histograms and fitted for each resonator independently with

![Figure 2](image-url)
a Gaussian distribution \( P(\Delta \kappa) = A \cdot e^{-((\Delta \kappa - (\Delta \kappa_f))/\sigma)^2/2\sigma^2} \) in order to localize the center \((\Delta \kappa_f)\) as shown in Fig. 3(b). The fits show that the deviation of the center from 0 is of the order \(1\% \) of the linewidth. For two of the fits (green and red) the 0 is within the 95\% confidence interval of the fit for one (dark blue) the full confidence interval is below 0 and for the last (light blue) it is above 0. This shows that there is no significant lasting effect of the radiation dose used. The widths of the distributions from the fits vary between 10 and 20 MHz. This spread of the distribution is caused by the dependency of the exact shape of the resonance on the polarization and interference effects which cause distortions of the lineshape. Examples of data and fits are shown in Fig. 4.

The measurements in Fig. 4(a) look very similar but show a significant deviation in the result of the fit. Although the other measurements shown almost fall on top of each other for large parts, the fitted linewidths still deviate by some MHz. The measurement in Fig. 4(d) shows a split resonance which is fitted with an appropriate function as described above.

In conclusion we have shown that high-energy proton radiation does not lead to a degradation of silicon nitride microresonators for Q-factors of the order of \(10^6\). Their quality factor did not change due to the irradiation. This result can be applied to silicon nitride waveguides with a structure similar to the ones measured here. Our work therefore paves the way for the rather young platform of silicon nitride waveguides towards more integrated and robust devices in space applications. Such devices can be microresonator-based optical frequency combs.

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