Thermal and Structural Analysis of a Suspended Physics Package for a Chip-Scale Atomic Clock

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The power dissipation for chip-scale atomic clocks (CSAC) is one of the major design considerations. 12 mW of the 30 mW power budget is for temperature control of the vertical-cavity-surface-emitting laser (VCSEL) and the alkali-metal vapor cell. Each of these must be maintained at 70+/−0.1°C even over large ambient temperature variations of 0–50°C. Thus the physics package of a CSAC device, which contains the vapor cell, VCSEL, and optical components, must have a very high thermal resistance, greater than 5.83°C/m W, to operate in 0°C ambient temperatures while dissipating less than 12 mW of power for heating. To create such a high level of insulation, the physics package is enclosed in a gold coated vacuum package and is suspended on a specially designed structure made from Cirlex, a type of polyimide. The thermal performance of the suspended physics package has been evaluated by measuring the total thermal resistance from a mockup package with and without an enclosure. Without an enclosure, the thermal resistance was found to be 1.07°C/m W. With the enclosure, the resistance increases to 1.71°C/m W. These two cases were modeled using finite element analysis (FEA), the results of which were found to match well with experimental measurements. A FEA model of the real design of the enclosed and suspended physics package was then modeled and was found to have a thermal resistance of 6.28°C/m W, which meets the project requirements of greater than 5.83°C/m W. The structural performance of the physics package was measured by shock-testing, a physics package mockup and recording the response with a high-speed video camera. The shock tests were modeled using dynamic FEA and were found to match well with the displacement measurements. A FEA model of the final design, not the mockup, of the physics package was created and was used to predict that the physics package will survive a 1800 g shock of any duration in any direction without exceeding the Cirlex yield stress of 49 MPa. In addition, the package will survive a 10,000 g shock of any duration in any direction without exceeding the Cirlex tensile stress of 229 MPa. [DOI: 10.1115/1.4000211]

1 Introduction

The goal of the DARPA chip-scale atomic clock (CSAC) program is to fund development of an ultraminiaturized, low power, atomic time, and frequency reference unit. The unit would be available to integrate into devices to enable miniature and low power, high security ultra high frequency (UHF) communication, and jam-resistant global positioning system (GPS) receivers. The unit must display a frequency stability of $+/-1\times10^{-11}$ Allan deviation at 1 h integration time, achieve a size reduction of greater than 200 times, from 230 cm^3 to less than 1 cm^3, and a power reduction of greater than 300 times, from 10 W to less than 30 mW. Scientists at NIST-Boulder laboratories have demonstrated very impressive work in developing such a device based on coherent population trapping (CPT) [1]. This method utilizes a vertical-cavity-surface-emitting laser (VCSEL) to pass a modulated beam of light through a cell containing a vapor of cesium or rubidium atoms, henceforth, called a vapor cell.

The thermal management challenge of CSAC devices is different from typical portable electronics applications requiring the control of the maximum junction temperatures [2–4]. The frequency of light that the VCSEL emits is dependent on the temperature of the VCSEL [5]. The best measurement of the hyperfine transition frequency of the atoms in a vapor cell is attained at a specific, elevated temperature [1]. Thus, to create an accurate clock the temperature of the VCSEL and vapor cell must be maintained to within +/−0.1°C at all times during operation. The actual temperature to be maintained is dependent on the particular VCSEL chosen and the design of the vapor cell. For this discussion, we will choose to maintain the vapor cell and VCSEL at a temperature of 70.0+/−0.1°C. Thus, the thermal management goal is not to remove as much heat as possible but to maintain a specific temperature using as little power as possible.

Many other electronic devices must use temperature control to maintain device accuracy. Rahajandraibe et al. [6] presented excellent work to create a highly temperature stable, 10 ppm/°C, band-gap reference voltage, which is well suited for low power battery operated devices. Polymerase chain reaction (PCR) is a method to make many copies of a single strand of DNA, which has been shown to be feasible in a portable device. The process requires precise thermal cycling, +/−1°C, of the DNA solution to produce acceptable and rapid results [7]. Similarly, a review of portable gas and chemical sensors reveals that temperature control is critical for accurate and rapid analysis [8]. All of the above examples need to maintain temperature control while using as little power as possible if they hope to be suitable for portable devices.

Of course, other groups have examined the issue of thermal management for CSACs in particular. Kitching et al. [9] performed a thermal analysis of the physics package (vapor cell, VCSEL, and optics assembly with heaters for temperature control). They found that it requires 75 mW of power to operate the package. The majority of that power, 69 mW, is used to maintain the vapor cell at 80°C when the base temperature was 46°C.

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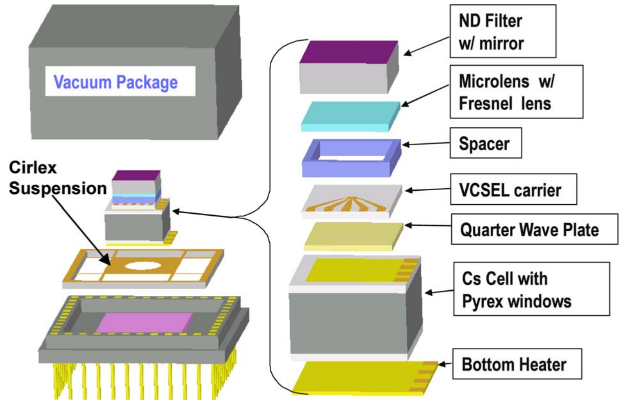

Fig. 1 Chip-scale atomic clock physics package designed by scientists at Teledyne Scientific Co. The cell and VCSEL in this assembly must be maintained at 70°C using heaters on either side of the cell with less than 12 mW of power. The physics assembly is suspended on a specially designed Cirlex suspension to limit conductive heat losses, coated in low emissivity coatings to limit radiation losses, and packaged in a vacuum to limit convective losses.

They identified five design improvements that should reduce power to run the physics package below 30 mW [9]. Mescher et al. [10] also considered the thermal management problem of CSAC devices. Their approach to reducing heating power for the physics package is to suspend it on two polyimide structures that offer a very small cross-sectional area for thermal conduction. They have demonstrated that their physics package design can be maintained at 75°C with an ambient temperature of 25°C using 7 mW of heating power. This equates to an impressive total package thermal resistance of 7.14°C/m W [10].

Our approach is similar to Mescher et al. [10] in that we treat the physics package as a discrete electronics component to be integrated with the local oscillator (LO) and control electronics on a standard printed circuit board (PCB). Figure 1 shows a physics package, suspension, and enclosure designed by Teledyne Scientific Co. This approach relies on a small amount of power (12 mW) to maintain the physics package temperature. To overcome a 70°C temperature gradient using less than 12 mW, the total thermal resistance of the physics package must be greater than 5.83°C/m W. Reaching this level of thermal isolation requires the elimination of convection by vacuum packaging, the minimization of radiation by using low emissivity coatings and the minimization of conduction through careful design of the package suspension and I/O wires. Thus, to limit conduction and radiation, the design of the physics package suspension is the highest concern. The design must be highly thermally resistive, it must minimize surface area to reduce radiation and it must survive inertial loading.

Polyimide has become a common material in electronics packaging and has been identified by Lutwak et al. [11] to be a possible material to create such a suspension because it can be cut to exacting tolerances or patterned using photolithography; it has a low thermal conductivity 0.2–0.17 W/m K and it has a relatively high yield strain of 3% [11].

Lutwak et al. [11] designed an impressive suspension in order to produce a physics package that uses less than 10 mW of power, which is less than 1 cm^3, has a first natural frequency above 2000 Hz, and can withstand a constant acceleration of 2200 g. The design uses two 5 μm thick polyimide suspensions. Each suspension has eight arms that are 375 μm wide, 1000 μm long, and are stretched out of plane to span from the physics package to the outer package of the assembly [10–12].

This paper describes the design and analysis of a Cirlex physics package suspension. The goal was to create a physics package that has a total thermal resistance greater than 5.83°C/m W, does not yield when loaded with a 1500 g, 0.5 ms shock, and has a first natural frequency above 2000 Hz. Thermal analysis shows that the total thermal resistance of the suspended and enclosed physics package is 6.28°C/m W. This means the physics package can be held at 70°C while the ambient temperature is 0°C using 11.14 mW. The structural analysis of the suspended physics package shows that the suspension will survive a 1800 g shock load of any duration in any direction without exceeding the yield stress of the Cirlex. These two results prove that this suspension design is a very good candidate for CSAC packaging.

2 Physics Package Suspension Design

The suspension design, shown in Fig. 2, was inspired by micro-electro-mechanical systems (MEMS) piston mirror suspensions. The suspension is laser cut from 30 mil (0.76 mm) thick Cirlex 3000 CL, which is a polyimide material. Two suspensions are used to keep the physics package from rocking when experiencing horizontal accelerations. This design minimizes outer package volume by wrapping the arms around the physics package. The arms of the suspension are very long so that I/O wires that are patterned on them are long and thermally resistive. The beams are designed in an hourglass shape so that the larger bending mo-

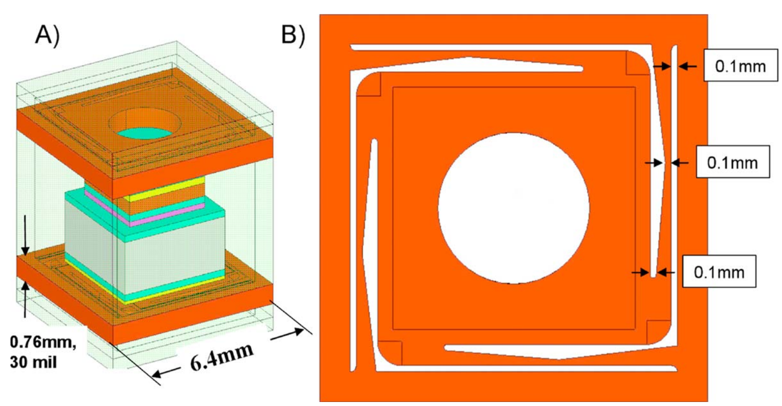

Fig. 2 (*a*) Suspension design to minimize the physics package volume. (*b*) The suspensions are made from two identical 30 mil thick Cirlex 3000 CL parts. Notice that this design will tend to unwind when a vertical force is applied. To stiffen the structure, the top suspension is reversed so that the two suspensions unwind against each other and utilize the strength of the solid physics package.

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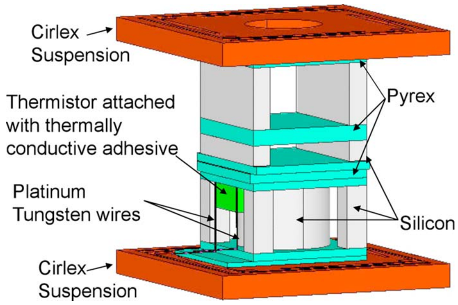

Fig. 3 Solid model of the mockup physics package provided to the University of Colorado by Teledyne Scientific Co. The thermistor was attached, using thermally conductive adhesive, to the cell in order to heat and sense the temperature of the package.

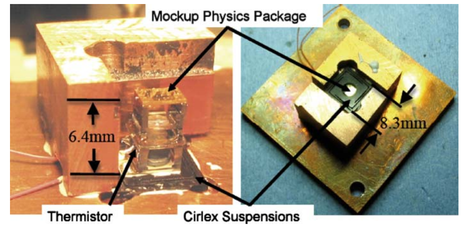

Fig. 4 Mockup physics package suspended on two Cirlex pieces and mounted in a polished copper enclosure. A thermistor mounted to the side of the physics package was used to heat the physics package and sense the temperature of the package.

ments experienced at the beam-ends are spread over more material. This reduces stresses caused by vertical accelerations but still maintains a high thermal resistance. The inner volume of the enclosure is about 0.2 cm^3.

Notice from the design taken separately that the suspension pieces will tend to unwind if a vertical force is applied. To keep this from happening, the top suspension is reversed from the bottom suspension although the part is the same. This causes the top to unwind in the opposite direction from the bottom. The result of this is that neither can unwind since the physics package is stiff and the beams act as fixed-fixed beams. When this design is loaded in the horizontal direction, one beam on each of the suspensions, on opposite sides, is loaded in tension, which results in a very stiff structure. The thermal and structural analyses of this design will be reviewed in detail in the following sections.

3 Thermal Analysis

To characterize the thermal performance of the physics package with the suspension design created to minimize volume, described in the previous section, Teledyne Scientific Co., had sample Cirlex 3000 CL suspension lasers cut by Laser Light Technologies Inc. Teledyne decided that initially, assemblies would be easier to create if the suspensions were scaled up to 130% of the designed size (Fig. 2). Although the design was scaled up, the thickness of the Cirlex, 30 mil or 0.76 mm, was maintained. Two of these suspension pieces, as well as mockup of the physics package and shown in Fig. 3, were supplied to the University of Colorado to carry out the thermal and structural experimentation.

As stated previously, the VCSEL and vapor cell must be maintained at 70°C during clock operation. The clock must use less than 30 mW of power to run the control electronics and maintain temperature control. Teledyne Scientific Co., has decided that, with their control electronics design, there should be 12 mW available for heating of the physics package. The lowest ambient temperature that the clock may experience is 0°C. Therefore, the total thermal resistance between the suspended portion of the physics package to the outside of the package enclosure must be greater than 5.83°C/m W. The suspension is designed so that the heat conducted away from the physics package must travel a long and resistive path to leave the package. The design was also created to minimize the outer volume of the package, which minimizes the interior surface area, thus reducing the amount of radiation between the physics package and enclosure. To determine the thermal resistance of the suspended package, measurements of the thermistor temperature versus input power were made using the mockup physics package with and without a polished copper enclosure. These cases were then modeled using FEA and the final design case was also modeled to determine whether the design meets the thermal resistance requirement.

Figure 4 shows the mockup physics package with two suspension pieces in a copper assembly. The physics package was attached to the suspensions and the suspensions were attached to the copper assembly using Dow Corning 3—1818 thermally conductive adhesive (1.8 W/m K). The copper assembly was designed to maintain the outer frames of the suspension pieces at room temperature and provide an enclosure for the package to reflect as much radiation as possible. A 6.8 k Ω surface mount thermistor was glued to the physics package against the cell, as shown in Fig. 3. Two 1 mil diameter platinum tungsten wires (10 W/m K) were soldered to the thermistor contacts and the other ends were glued to the outer frame of the bottom Cirlex suspension. These two ends were soldered to copper wires to make electrical connections with the power supply. Conduction through the I/Os was reduced substantially by using the platinum wires. Two cases were examined. First, the physics package was mounted with two suspension pieces to the copper base. The copper base maintained the outer frame of the bottom suspension at room temperature (23.1°C). The package was not enclosed and the top suspension was not in contact with anything. For the second case, the enclosure was put around the package. In this case, the top suspension was glued to the enclosure. The copper enclosure maintained the outer frames of both the suspensions at room temperature. In both cases the assembly was bolted into a vacuum chamber equipped with a turbo pump. The experiments were conducted at a pressure of approximately 10^{-6} mbar. At this pressure convection from the device is effectively eliminated. To perform an experiment, voltage was supplied to the thermistor to heat the physics package. The voltage needed to be monitored and adjusted constantly since the resistance of the thermistor decreased as it was heated, which increased the amount of power going to the thermistor. This adjustment was made to heat the thermistor to temperatures from room temperature up to 100°C. The data were recorded only after the voltage and current, and thus, the power remained constant for at least 2 min.

Figure 5 shows the temperature difference between the thermistor and room temperature versus the power dissipated by the thermistor for the package with no enclosure and two separate assemblies of the package with an enclosure. Finite element simulations of the two cases are also presented and will be explained in the following paragraphs. The thermal resistances for the maximum power for the three experiments are 1.07°C/m W with no enclosure, 1.35°C/m W for one of the enclosed package experiments, and 1.71°C/m W for the other enclosed package experiment. The enclosure increased the overall thermal resistance, even though it creates a new conductive heat path out through the top suspension, because it reflects some of the radiated heat. These measurements show a much lower thermal resistance than what is required. The thermal isolation can be increased by improving the enclosure reflectivity and coating the physics package with a reflective material such as gold. These improvements will be explored using finite element analysis and will be discussed in the following section.

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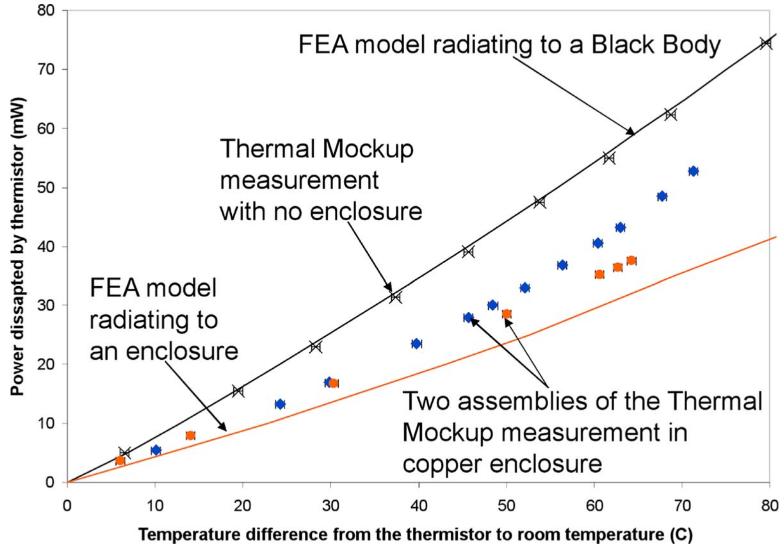

Fig. 5 Power dissipated by the thermistor mounted to the mockup physics package versus the temperature difference created between the thermistor and room temperature. The thermal resistances are calculated for maximum power points by dividing the temperature difference by the power and are found to be 1.07°C/m W with no enclosure, 1.35°C/m W for one of the enclosed package tests, and 1.71°C/m W for the other enclosed package test.

Two 3D thermal finite element models of the previously mentioned experimental cases were created using ANSYS, as shown in Fig. 6. Table 1 lists the thermal conductivities and emissivities of the materials used in the two models. The copper enclosure had some surfaces that were polished and others that were rough and coated in buffing compound and so these are listed separately in the table. Thermal conductivities for the Pyrex, silicon, and the thermistor were decreased to account for the low conductivity glue that holds the structure together.

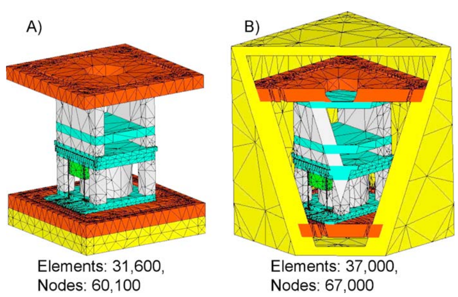

Fig. 6 3D thermal finite element models created to simulate the two experimental cases: (*a*) without an enclosure and (*b*) with a polished copper enclosure.

Table 1 Thermal conductivity and emissivity for the different materials used in the thermal finite element models of the two experimental cases

Material	Thermal conductivity (W/m K)	Total hemispherical emissivity
Pyrex	0.5	0.82
Silicon	80	0.6
Cirlex	0.17	0.86
Thermistor	0.7	0.95
Platinum tungsten wire	10	0.03
Polished copper	390	0.1
Rough copper	390	0.95

The FEA results are presented with the experimental results in Fig. 5. For the mockup radiating to space or a black body enclosure, the model predicts the power consumption very well. In the case of the copper enclosure, the model predicts the power to be lower than measured in the experiments. This is likely because the emissivity of the polished copper was lower than the model's assumption. In addition, the real copper enclosure had gaps along its edges, which account for a small surface area but would act as nearly black surfaces and could absorb a significant amount of power. Figure 7 shows typical temperature contours for the two cases. From the figure, it can be seen that heat from the thermistor was not transferred into the package as efficiently as was hoped because of the low thermal conductivity of the adhesive used to attach the thermistor to the package. In addition, in the case without an enclosure, it can be seen that the top suspension radiates a significant amount of heat to the environment since is has a large surface area and high emissivity. These models match well with the experimental data, thus the design case may be modeled using the same techniques to see if the package can meet the thermal resistance requirement of greater than 5.83°C/m W.

To conclude the thermal analysis of the physics package design, a 3D thermal finite element model of the real physics package design suspended on the design-sized, not scaled up as above,

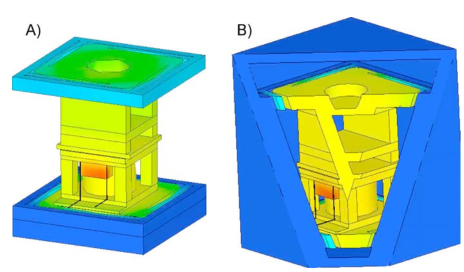

Fig. 7 Typical temperature contours for the two modeled experimental cases: (*a*) no enclosure and (*b*) polished copper enclosure. The resistance of the thermally conductive adhesive allows a large temperature gradient between the thermistor and the package.

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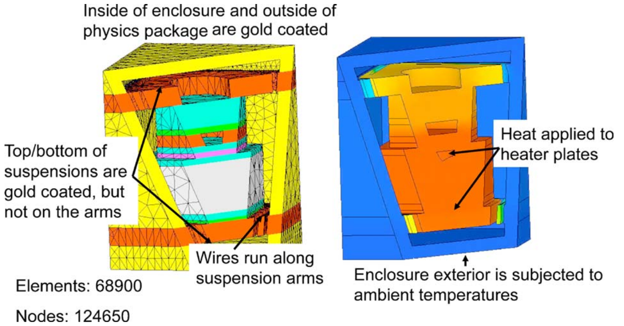

Fig. 8 3D thermal finite element model of the design case physics package and suspension. Low emissivity coatings are used to minimize radiation. Vacuum packaging eliminates convection. Conduction occurs through the suspension and through wires on the arms of the bottom suspension. Heat is applied on either side of the cell using clear resistance heaters. The overall thermal resistance is 6.28°C/m W, which meets the project goal.

Cirlex suspensions was created with an enclosure and is shown with a temperature contour in Fig. 8. The model assumes vacuum packaging, which eliminates convection. The inner surfaces of the enclosure and the outer surfaces of the physics package are assumed to be gold coated $\varepsilon=0.03$ to minimize radiation. Similarly, the top surface of the inside square section of the top suspension is gold coated as well as the bottom of the bottom suspension. The arms of the suspensions cannot be gold coated because the gold would conduct heat along the arms. Gold wires, however, are patterned on the four arms of the bottom suspension to provide I/Os for the package. These wires are modeled as a single thick wire on each of the four bottom suspension arms. This thick wire was created so that it has the same cross-sectional area as three 2 μm thick, 20 μm wide wires. This way the package can have up to 12 I/Os but the model is maintains its simplicity. Heat was applied to two heater plates on either side of the cell. The heater plates use clear resistance heaters made of indium tin oxide. By applying 10 mW of power to the model, the cell temperature was found to reach 62.8°C, which translates to an overall package resistance of 6.28°C/m W. This is greater than the specified 5.83°C/m W target. The model can also be used to find the resistances for each of the three heat paths: conduction through the suspensions of 45°C/m W, conduction through the I/O wires of 35°C/m W, and radiation of 9.2°C/m W. These three resistances act in parallel to give the overall resistance. The values show that 68% of the heat lost is through radiation even with the serious steps taken to minimize it. Unfortunately, the Cirlex material has a high emissivity $\varepsilon=0.86$ and even though most of the structure is gold coated the suspension arms are able to radiate to themselves. If a substitute material with a lower emissivity were used or a coating of gold were put on the sides of the inner and outer pieces of the suspension the radiation could be significantly reduced.

4 Structural Analysis

Vertical and horizontal shock testing was accomplished using the mockup physics package mounted between the two suspensions, shown in Fig. 9. Shock loads were created using a Lasnmont 15D shock-testing apparatus. The acceleration of the shock table was measured using a shear mode integrated circuit piezoelectric (ICP) accelerometer from Piezoelectronics Inc. The outer frames of the suspensions were clamped into an assembly to fix them to the shock table while allowing the physics package to move on the suspension. The displacement of the mockup physics package was captured with high-speed videography using an Olympus I speed camera capable of capturing video at up to 33,000 frames per second (fps).

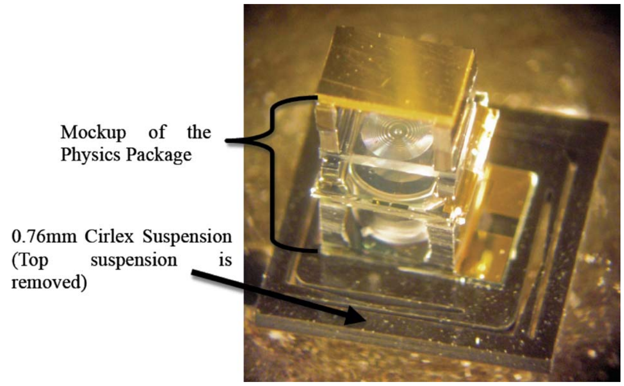

Fig. 9 Mockup physics package built by Teledyne Scientific Co., mounted between two 30 mil thick Cirlex suspensions.

To measure the displacement of the mockup physics package, high-speed video of a 2000 g, 0.32 ms vertical impact was captured. A microruler was created from a plastic mask used for photolithography and was glued to the inside of the window in the clamping assembly in close proximity to the physics package. The black lines on the clear microruler are 640 μm from center to center. As an example of the high-speed footage, Fig. 10 shows four screen shots from a video shot at 6000 fps. Frame 0 is just prior to impact. In frame 4, the physics package is displaced downward with respect to the clamping assembly and the microruler and is then displaced upward with respect to the ruler by frame 6. Then by frame 8 the physics package has moved back downward as it vibrates up and down. Notice that the entire clamping assembly is first moving downward with respect to the camera frame and is then moving upward with respect to the camera frame after impact.

To acquire usable data from the high-speed footage, a video of the impact taken at a 33,000 fps was captured. The video was then expanded to full screen and the distance from the edge of the camera frame to a fixed point on the microruler and a fixed point on the physics package were measured for each frame. By using the known distances on the microruler, it was found that each millimeter on screen was equal to 11.8+/−0.2 μm. Since the video was shot at 33,000 fps, the time between each frame is

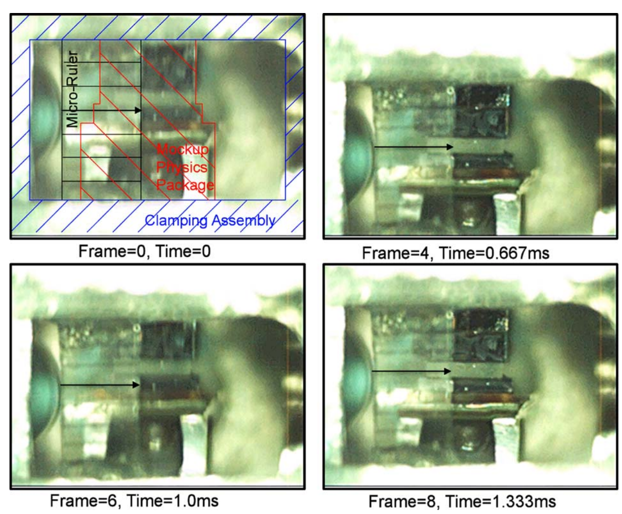

Fig. 10 Four frames taken from high-speed video of the mockup physics package, shot at 6000 fps, during a 2000 g, 0.32 ms vertical impact. Frame 0 is highlighted to show the physics package, microruler, and clamping assembly. The divisions on the microruler are 640 μm from center to center.

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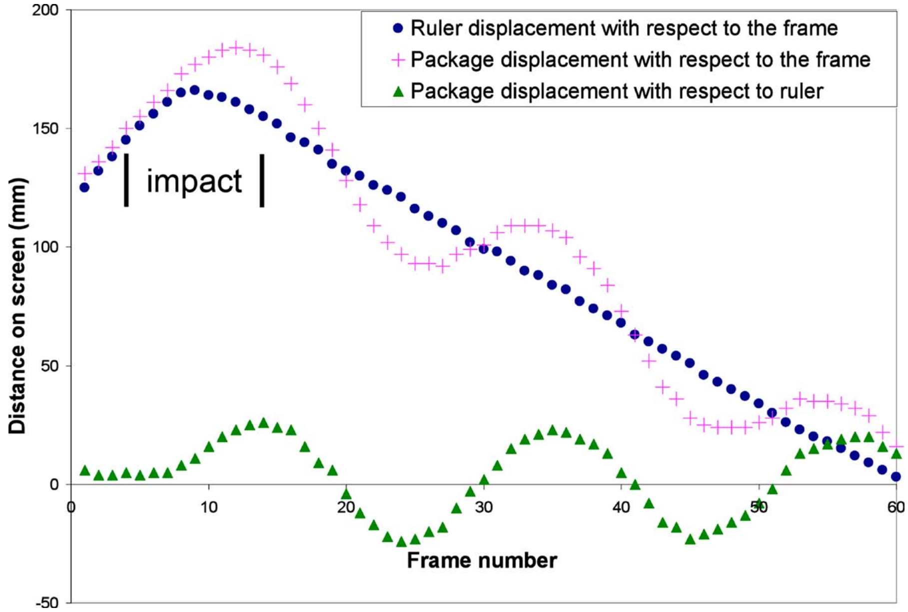

Fig. 11 Displacement measurements made from a high-speed video clip of a 2000 g, 0.32 ms vertical impact of the mockup physics package. The time between frames is 0.0303 ms and 1 mm on screen is equal to 11.8±0.2 μm. By measuring the displacement of the ruler, fixed to the impact table, with respect to the frame and the displacement of the package with respect to the frame, the displacement of the package with respect to the impact table can be found.

$1/33,000=0.0303$ ms. Figure 11 shows the measurements made from the video as well as the difference between the displacement of the ruler, which is fixed to the impact table, and the package. This difference is the package displacement with respect to the impact table or the inner square part of the suspension with respect to the outer frame of the suspension. By converting the distance measured on screen into actual distance and converting frame number to time, one can find that the package vibrates at a frequency of $1535+/-35$ Hz and the maximum displacement of the package with respect to the impact table is $0.30+/-0.02$ mm. A detailed discussion of these results will be carried out below.

A similar experiment was attempted to measure the response of the mockup physics package to horizontal impacts. No useful data could be extracted from the video because although displacement and vibration are perceivable in the footage, they are too small to measure with sufficient accuracy.

The final set of shock experiments carried out were an attempt to cause a failure of the suspension. The mockup physics package was subjected to ten repeated 9000 g, 0.12 ms horizontal impacts and ten repeated 8150 g, 0.13 ms vertical impacts. This level of acceleration was chosen because it is near the limit of the accelerometer. No failure or perceivable yielding of the suspension was observable. These tests have been modeled to understand the stresses in the suspensions.

Two 3D dynamic structural finite element models were created using ANSYS for modal and dynamic analysis of the suspended mockup physics package and the design physics package. Each model was meshed with ten node tetrahedral implicit structural elements, SOLID92. Illustrations of the models are shown in Fig. 12 along with the number of elements and nodes associated with each model and the total model mass. The top and bottom of the outside frame of both the top and bottom suspensions was fixed in all degrees of freedom. Thus, the initial displacement and velocity of the models is zero with respect to the shock table. A time varying acceleration was then applied to the model with a small enough time resolution to acceptably match a versed-sine input shock. The model was then solved for a period prior to and after the shock with enough time resolution to capture structural displacement. The displacement output of the model is displacement with respect to the suspension frame, which is clamped to the shock table of the shock-testing machine.

A 2000 g, 0.32 ms vertical shock of the suspended mockup physics was measured with the high-speed camera observation and was modeled using FEA. The results are presented with the camera measurements in Fig. 13. It can be seen that the model prediction corresponds very closely with measured displacement. Thus, this model can be used to predict the stress in the suspension for a variety of vertical and horizontal shocks in this case and in the design case.

Figure 14 shows two pictures of the mockup physics package modeled with the Von Mises stress contours displayed. The meshes of the high stress areas are also shown. The stresses at this mesh size are near mesh independent. As seen from the figure, in vertical loading all eight suspension beams are put into fixed-fixed bending. The maximum stresses occur at the beam-ends with a concentration at the small radius where the beams connect to the inside of the suspension. In horizontal loading, two beams are loaded under tension, two beams are loaded in compression, and

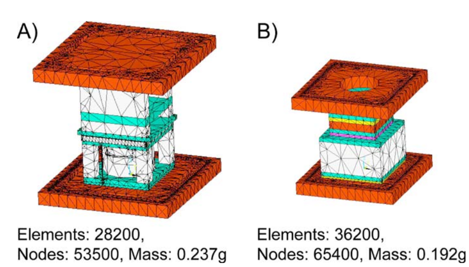

Fig. 12 Dynamic finite element models created to study the (*a*) mockup physics package subjected to vertical and horizontal shocks and the (*b*) final design physics package and suspension subjected to vertical shocks, horizontal shocks, and modal analysis.

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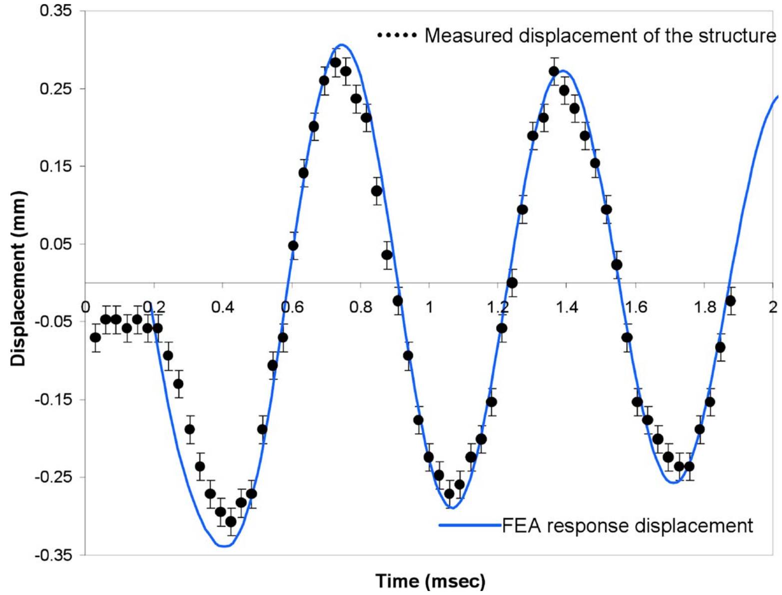

Fig. 13 Displacement of the suspended mockup physics package, subjected to a 2000 g, 0.32 ms shock, measured from high-speed video footage compared with a FEA model. The uncertainty in the video measurements corresponds to +/−1.5 mm measured on screen, which corresponds to +/ −0.0177 mm of displacement.

the other four are loaded in bending. Using the model, the maximum Von Mises stress found for the 8150 g, the vertical acceleration was 127.4 MPa, the maximum stress for the 9000 g, and horizontal acceleration was 137.0 MPa. The static yield stress for Cirlex is 49 MPa while the static tensile strength is 229 MPa. Thus, while the tests caused the maximum stress to exceed the static yield stress it did not exceed the static tensile stress. This is why the structure did not fail even after the ten repeated 8150 g vertical and ten repeated 9000 g horizontal tests. No yielding could be observed but it is possible that the suspension is yielding and may fail eventually if the testing was repeated continuously.

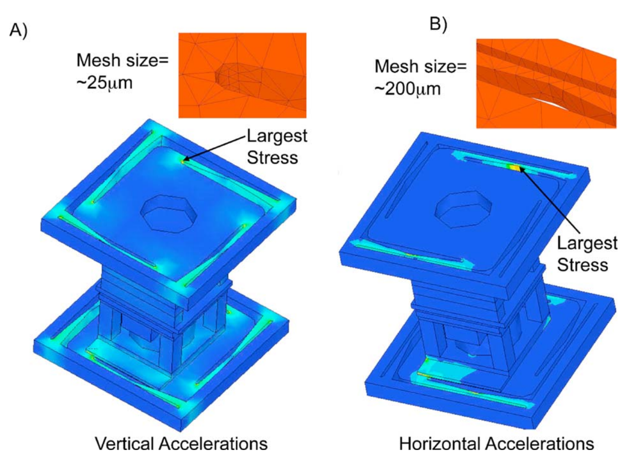

Fig. 14 Typical stress distributions for (*a*) vertical or (*b*) horizontal accelerations of the suspended mockup physics package. In vertical loading all eight suspension beams are loaded as fixed-fixed bending beams. The maximum stresses occur at the beam-ends. In horizontal loading, two beams are loaded under tension, two beams are loaded in compression and the other four are loaded in bending. The maximum stress occurs at the neck of the beams that are in tension.

For this analysis this result is very promising and shows the excellent capacity of the suspensions to withstand very high accelerations.

The FEA model of the design-sized physics package was first used to perform a modal analysis of the structure to find the first seven mode shapes and corresponding frequencies. The results of these analyses are listed in Table 2. The first three modes are of the greatest concern since they have the lowest frequencies and will thus be the first modes to resonate if the input vibration nears these frequencies. The goal was to have the first natural frequency above 2000 Hz, which was achieved using 30 mil thick Cirlex suspensions. If the requirement is raised to 3000 Hz, the top suspension can be switched to Cirlex 5000 CL, which is 50 mil thick or 1.27 mm. This will raise the first natural frequency to 3100 Hz and increase the higher mode shape frequencies slightly.

Next, a dynamic analysis for a vertical (2000 g, 0.25 ms, 10,000 g, 0.25 ms, and 1500 g, 0.5 ms) and horizontal (2000 g, 0.075 ms and 10,000 g, 0.075 ms) versed-sine shock input was performed for the design case. Von Mises stresses for the structure over time can be found using the model. Figure 15 shows the stress contours for the design case physics package model loaded vertically and horizontally. The meshes of the high stress areas are also shown. The stresses at this mesh size are near mesh independent.

Table 3 gives the maximum Von Mises stresses found for each of the preceding modeled cases. In the required case of 1500 g,

Table 2 A modal analysis of the suspended physics package design is listed along with the type of vibration: The analysis shows the first natural frequency is above the required 2000 Hz

Mode No.	Mode shape	Frequency (Hz)
1	*Z*-axis vertical vibration	2134
2 and 3	*X*- or *Y*-axis horizontal vibration	6645
4 and 5	Rotation about the *X*- or *Y*- axis	8622
6	Rotation about the *Z*-axis	13,073
7	Vibration of the beams on the *X*-*Y* plane	25,749

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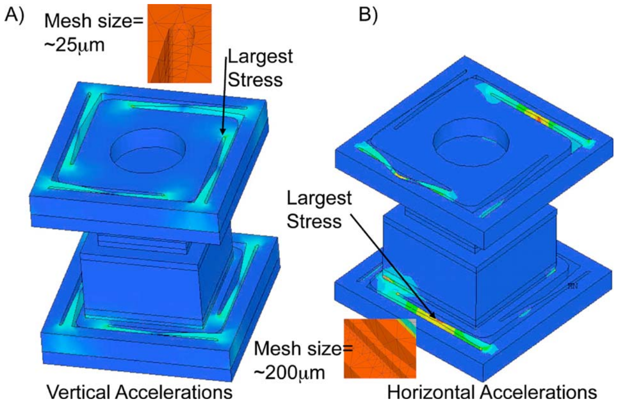

Fig. 15 Contours of the Von Mises stresses developed in the structure for either (*a*) vertical accelerations or (*b*) horizontal accelerations. For similar amplitude accelerations the stress is higher in the vertical case because the beams are in bending as opposed to tension in the horizontal case.

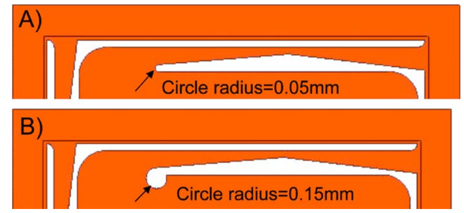

Fig. 16 Radius at stress concentration point was increased to reduce stress caused by a 1500 g, 0.5 ms shock. The maximum stress must be below the static yield stress of Cirlex σ_y =49 MPa. This change will have a negligible impact on the total thermal resistance and first natural frequency of the package.

0.5 ms, it was found that the maximum stress, 67.5 MPa, which is above the static yield stress σ_y=49 MPa of Cirlex. While this is raises concerns, it is apparent that the majority of the experimental shock-testing likely produced stresses above the static yield stress of the Cirlex but never exceeded the static ultimate tensile strength of the Cirlex σ_{ut}=229 MPa. Over one hundred shock tests on a single pair of suspensions that should have produce stresses over the yield stress were carried out during this study. After all of the testing, the suspensions were examined under a microscope, and showed no visible signs of damage. Two possible explanations for the lack of visible damage can be postulated. First, there *is* damage and continued testing at these levels would eventually cause a catastrophic failure. Second, the material yield stress is stain rate dependent, like many other materials, and the dynamic yield stress is much higher than the static yield stress. The dynamic yield stress may even approach the ultimate tensile stress for high strain rates, just as other materials tend to [13]. Unfortunately, the dynamic material properties of Cirlex have not yet been well documented. Thus, the design may be better accepted if the static yield stress is not exceeded for the required 1500 g, 0.5 ms shock. To meet this requirement, the stress concentration that produces the maximum stress needs to be alleviated by enlarging the radius at that joint, as shown in Fig. 16. This change will cause a negligible impact on the thermal characteristics of the package. The first natural frequency of the structure is reduced from 2134 Hz to 2052 Hz, which is still above the design benchmark of 2000 Hz. By making this adjustment the maximum yield stress caused by a 1500 g, 0.5 ms vertical shock will be reduced from 67.5 MPa to 43.9 MPa, which is below the static yield stress for Cirlex.

Table 3 Summary of maximum Von Mises stresses found for each of the dynamic models

Type of mass	Input acceleration (g), (ms)	Maximum Von Mises stress (MPa)
Mockup	Vertical: 2000, 0.32	94.8
Mockup	Vertical: 8150, 0.13	127.4
Mockup	Horizontal: 2000, 0.25	29.3
Mockup	Horizontal: 9000, 0.12	137.0
Design	Vertical: 2000, 0.25	78.8
Design	Vertical: 10,000, 0.25	436.5
Design	Vertical: 1500, 0.5	67.5
Design	Horizontal: 2000, 0.075	34.2
Design	Horizontal: 10,000, 0.075	151.1
Adjusted design	Vertical: 1500, 0.5	43.9

A quicker way to decide what level of shock is acceptable is to load the model statically instead of dynamically. In the dynamic case, shocks with durations close to the natural period of vibration in that direction can cause dynamic amplification of the acceleration. This amplification, however, will not exceed 1.77 for simple shocks [14]. Thus, if the model is solved statically, a similar stress will be produced if the input static acceleration is multiplied by 1.77. This method greatly reduces computation time. Using this method, the maximum acceptable acceleration, assuming the worst-case scenario duration, to produce a maximum stress equal to the yield stress and the ultimate tensile stress can be found. For the adjusted design subjected to vertical shocks, the worst-case duration the shock of 1800 g will cause a stress equal to the yield stress and a shock of 10,100 g will cause a stress equal to the ultimate tensile stress. Subjected to horizontal shocks of the worst-case duration, a shock of 2200 g will cause a stress equal to the yield stress and a shock of 10,700 g will cause a stress equal to the ultimate tensile stress. Thus, the adjusted suspension design complies with the specification of a 1500 g, 0.5 ms shock. Furthermore, it is likely that the structure could sustain many shocks up to 1800 g of any duration in any direction without yielding and could survive a singular shock of up to 10,000 g of any duration in any direction. The structure also has a first natural frequency above 2000 Hz; therefore, lower frequency vibrations will not cause resonance.

5 Conclusions

A suspended physics package design has been created to maintain the vapor cell and VCSEL of a chip-scale atomic clock at 70°C, with a minimum ambient temperature of 0°C, using less than 12 mW. The suspension design is of critical concern and its thermal and structural properties were analyzed through experiments and finite element modeling. The physics package design has a total thermal resistance of 6.28°C/m W. This means the physics package can be held at 70°C while the ambient temperature is 0°C using 11.14 mW. In addition, the suspended physics package will survive a 1800 g shock load of any duration in any direction without exceeding the yield stress of the suspension material, Cirlex. The design also has a first natural frequency above 2000 Hz. These three results show that this suspension design is a very good candidate for CSAC packaging.

Acknowledgment

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