A "TURN-KEY" OPTOELECTRONIC OSCILLATOR WITH LOW ACCELERATION SENSITIVITY

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ABSTRACT

We present the experimental results of the first fully packaged optoelectronic oscillator module operating at 11GHz. We demonstrate a fiber delay line management technique that reduces the acceleration sensitivity of the module by 40 times. With measured acceleration sensitivity less than 1.5×10^{-10}/g, this oscillator is believed to have the lowest acceleration sensitivity of any oscillator directly operating at 10 GHz and above.

INTRODUCTION

Acceleration sensitivity is an important specification for oscillators, especially for those to be used in moving objects, such as automobiles, ships, aircraft, and satellites. For example, in a satellite communication system, a 10-time reduction in acceleration sensitivity of the oscillator in a transponder can result in more than 12 times increase in number of users serviced by the transponder [1]. Therefore, the economic impact of a low acceleration sensitive oscillator can be significant, especially for mobile communication systems.

Although the optoelectronic oscillators (OEO) [2] has been anticipated to be insensitive to acceleration, its acceleration sensitivity has never been studied or measured systematically. We show in this paper that the low acceleration sensitivity is among other attractive properties of the OEO, including high spectral purity, low phase noise, high frequency generation capability and dual electrical and optical interfacing and output capability. In particular, we report on a fully packaged OEO operating at 11 GHz that has an exceptionally low acceleration sensitivity of 1.5×10^{-10}/g. We find that a proper fiber coil arrangement is critical to achieve this low acceleration sensitivity and demonstrate a delay line management technique that is responsible for more than 40 times acceleration sensitivity improvement.

THE FULLY PACKAGED OEO

For acceleration studies, a rugged, compact and fully packaged OEO module with all components firmly mounted is required. The block diagram of the module is shown in Fig. 1. The module consists of a DFB laser and a feedback circuit including a semiconductor Mach-Zehder modulator, an optical fiber delay line, a photodetector, an electrical amplifier, and an electrical bandpass filter. The DFB laser and the modulator are integrated on the same chip and all the components used are identical with that in [3]. The module, which includes an electronic controller for driving the laser, biasing the modulator and the detector, controlling the laser temperature, and powering the microwave amplifier, are shown in Fig. 2 and it measures only 10 x 10 x 12 cm ^{3}. It is believed to be the first fully packaged "turn key" OEO to date. The nominal output RF power at 11.763 GHz is about +9 dBm and the total electrical power consumption is 5.5 watts. The phase noise spectrum of the OEO module with 2-km fiber delay is shown in Fig. 3. It is on the same level as the un-packaged breadboard OEO reported in [3], however at 10 kHz from the carrier, is about 20 dB higher than the OEO built with a diode pumped YAG laser. Lower phase noise can be readily obtained with increased delay length.

OEO ACCELERATION SENSITIVITY MEASUREMENT

The setup for OEO acceleration sensitivity measurement is shown in Fig. 4. The center of the setup is a vibration table that vibrates horizontally from left to right and can generate a maximum acceleration of 1.5g. In order to fully characterize the acceleration properties of the OEO, we must mount the OEO firmly on the vibration table in three different orientations. As shown in Fig. 4a, if the OEO is mounted on the table such that the Y-axis is along the vibration axis of the table, the measured acceleration sensitivity will be denoted Γ_Y. Similarly, when the X or the Z axis is aligned with the vibration axis, the corresponding acceleration sensitivity would be denoted as Γ_X or Γ_Z. It should be pointed out that both the power supply cable and the OEO output RF cable connecting the OEO on vibration table to the power source and measurement equipment should be carefully arranged so that their contributions to the measurement are minimized. We measure the vibration induced sideband with a HP 8563E spectrum analyzer and then calculate the acceleration sensitivity Γ_i of the OEO along axis *i* using [4]:

$$\Gamma_i = \frac{2 f_v}{A_i f_o} 10^{R/20} \tag{1}$$

Where f_v is the vibration frequency, A_i is the acceleration along axis *i*, f_o is the carrier frequency, and R is the carrier to sideband ratio. In the experiment, we either keep the vibration frequency constant while varying the acceleration from 0 to 1.2 g, or keep the acceleration constant while changing the vibration frequency from 10 to 100 Hz.

We first used a 2-km fiber coil as the delay line for the OEO. The coil has a diameter of 9.5 cm and a height of 6 cm. It was fabricated with standard communication (non-dispersion shifted) single mode fiber (Corning SMF-28) with a total insertion loss less than 0.5 dB. Our experiments indicates that the acceleration sensitivities along the X and Y axes are extremely low, about $1\text{x}10^{-10}$/g. On the other hand, the acceleration sensitivity along the Z axis is more than 20 times higher. Further experiments indicates that fiber management plays an important role for OEO's acceleration sensitivity and that the relatively high acceleration sensitivity along the Z axis can be greatly reduced with proper fiber coil management. We show both analytically and experimentally in the next section that we can accomplish such a reduction by splitting the fiber into two coils and mount them symmetrically on the OEO case.

OEO ACCELERATION ANALYSIS

When an oscillator is under a steady acceleration, its oscillating frequency will be shifted from the original oscillating frequency f_o. The operation frequency of the oscillator under acceleration can be expressed as [4]:

$$f(\vec{a}) = f_o(1+\vec{\Gamma}\cdot\vec{a}) \qquad (2)$$

where Γ is the acceleration sensitivity vector of the oscillator, and **a** is acceleration vector. For an OEO, the acceleration sensitivity can be related to the acceleration induced signal path length change by:

$$\vec{\Gamma}\cdot\vec{a} = \frac{\Delta f}{f_o} = -\frac{\Delta L}{L}, \qquad (3)$$

where $\Delta f \equiv f(\vec{a}) - f_o$ is the acceleration induced frequency shift and L is the total signal path length in OEO's feedback loop. Because the fiber length L_{fiber} dominates the signal path length in the OEO feedback loop, we obtain:

$$\frac{\Delta L}{L} = \frac{\Delta L_{fiber} + \sum_i \Delta L_i}{L_{fiber} + \sum_i L_i} \approx \frac{\Delta L_{fiber}}{L_{fiber}}, \qquad (4)$$

where ΔL_{fiber} is the fiber length change, L_i and ΔL_i are the signal path length and the corresponding path length change of each individual component inside the OEO feedback loop. Therefore, fiber's acceleration sensitivity dominates OEO's acceleration sensitivity and one needs to pay careful attention to how the fiber coil is arranged.

In general, for an OEO with a multiple connected fiber coils subject to a sinusoidal acceleration $\vec{a} = \vec{A}\cos(2\pi f_v t)$, where **A** and f_v are acceleration amplitude and frequency respectively, its output frequency can be expressed as:

$$f(\vec{a}) = f_o[1+\sum_i \vec{\Gamma}_i \cdot \vec{A}\cos(2\pi f_v t + \phi_i)], \qquad (5)$$

where Γ_i is the acceleration sensitivity of each fiber coil and ϕ_i is the relative phase of the fiber coil when it reacts to the sinusoidal acceleration. The phase can be made sufficiently small if the coils are mounted rigidly together. It can be seen from Eq. (5) that for a simple case of two connected fiber coils, if the signs of the acceleration sensitivity of the two are the same, they will add up and produce an increased total acceleration sensitivity. On the other hand, when the signs of the two are opposite they will cancel each other out, resulting in a decreased total acceleration sensitivity. The former situation can be realized by simply cascading two fiber coils as shown in Fig. 5 (equivalent to making a fiber coil of added length), while the latter situation can be realized by a symmetric arrangement shown in Fig. 6. If the two fiber coils are identical, complete acceleration cancellation in a particular direction can be achieved, assuming that the coils are rigidly mounted so that their relative phase $\Delta\phi = \phi_1 - \phi_2$ is zero. From Eq. (5), the output from the OEO for the case of two coils can be expressed as:

$$\begin{aligned} V(t) &= V_o \cos[2\pi f_o t + \beta \cos(2\pi f_v t) - \alpha \sin(2\pi f_v t)] \\ &= V_o \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} (-1)^m J_n(\beta) \{ J_{2m}(\alpha) \cos[2\pi (f_o + (2m+n)) f_v] t \\ &+ J_{2m+1}(\alpha) \sin[2\pi (f_o + (2m+n+1)) f_v] t \} \end{aligned} \qquad (6)$$

where β and α are defined as:

$$\beta \equiv \frac{(\vec{\Gamma}_1 + \vec{\Gamma}_2 \cos\Delta\phi) \cdot \vec{A} f_o}{f_v} \qquad (7)$$

$$\alpha \equiv \frac{\vec{\Gamma}_2 \cdot \vec{A} f_o \sin\Delta\phi}{f_v} \qquad (8)$$

By carefully adjusting the fiber coils such that $\vec{\Gamma}_1 + \vec{\Gamma}_2 \cos\Delta\phi = 0$, the residual acceleration sensitivity from Eq. (5) will be:

$$\Delta\vec{\Gamma} = \vec{\Gamma}_2 \sin\Delta\phi\,, \qquad (9)$$

and the corresponding OEO output will be:

$$\begin{aligned} V(t)\big|_{\beta=0} &= V_o J_0(\alpha) \cos(2\pi f_o t) \\ &+ Vo \sum_{m=1}^{\infty} (-1)^{m+1} J_{2m-1}(\alpha) \{ \sin[2\pi (f_o + \langle 2m-1 \rangle f_v) t] + \sin[2\pi (f_o - \langle 2m-1 \rangle f_v) t] \} \\ &- Vo \sum_{m=1}^{\infty} (-1)^{m+1} J_{2m}(\alpha) \{ \cos[2\pi (f_o + 2m f_v) t] + \cos[2\pi (f_o - 2m f_v) t] \} \end{aligned} \qquad (10)$$

From Eq. (10) one may calculate the amplitudes of the modulation sideband induced by the acceleration.

EXPERIMENTAL VERIFICATION

To test out analysis above, we made two identical fiber coils 1 km each with Corning SMF-28 fiber. Each coil measures a diameter of 9.5 cm and a height of 2.5 cm and has an insertion loss less than 0.5 dB. We first measured the acceleration sensitivity of the OEO for the case of two cascaded fiber coils in a configuration shown in Fig. 5, and the results are shown in Table 1. As mentioned before, the acceleration sensitivity along the X and Y axes are about 40 to 60 times lower than that along the Z axis. Nevertheless, the total acceleration sensitivity is still about same as that of a AT-cut crystal [5] and mach better than that of a SAWR [6].

To reduce the acceleration sensitivity along the Z axis, we arranged the fiber coil in the configuration shown in Fig. 6. We then measured the acceleration sensitivity of the OEO and found that it is indeed greatly reduced for acceleration along the Z direction, by more than 40 times. The measurement results are shown in Table 2 and 3. The total acceleration sensitivity $\Gamma = \sqrt{\Gamma_x^2 + \Gamma_y^2 + \Gamma_z^2}$ is less than $1.5\text{x}10^{-10}$ per g, which is the lowest result for any oscillator directly operating at 10 GHz or above. We expect to improve the performance further with improved package and better fiber coil balance.

We also evaluated our measurement noise floor cause by the vibrating power cable and the RF output cable and found that it is significantly lower than the acceleration sensitivity of the OEO.

CONCLUSIONS

In conclusion, we reported a first fully package OEO at 11 GHz. We demonstrated both analytically and experimentally that optical fiber delay line is dominates the acceleration sensitivity performance of OEO and careful fiber coil arrangement is important for achieving low acceleration sensitivity. Using a novel fiber coil balance technique, we were able to improve the acceleration performance by more than 40 time. As a result, we obtained an unsurpassed low acceleration sensitivity of less than $1.5\text{x}10^{-10}$/g of any oscillators operating at 10 GHz and above. Further improvement is anticipated with improved package and better fiber coil balance.

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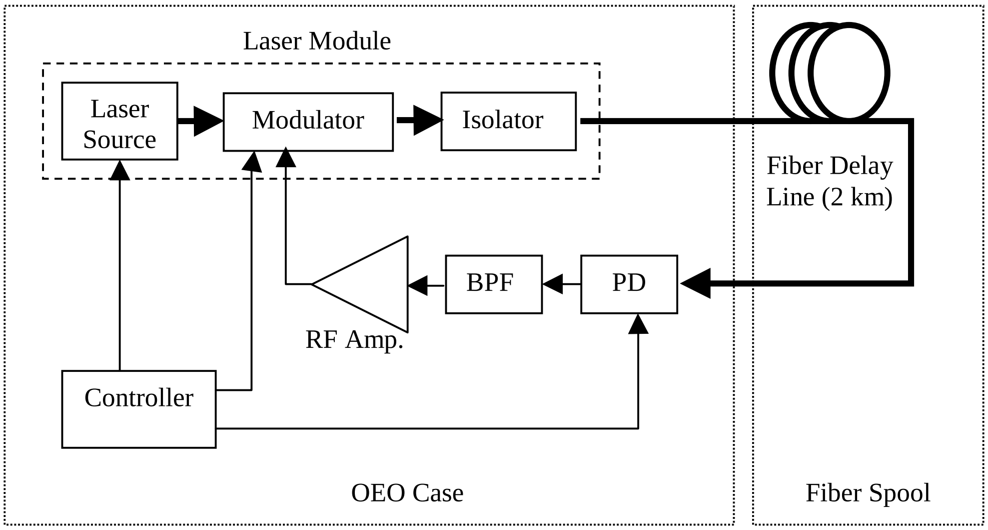


Fig. 1. An optoelectronic oscillator (OEO) block diagram. PD: Photodetector BPF: Bandpass filter.

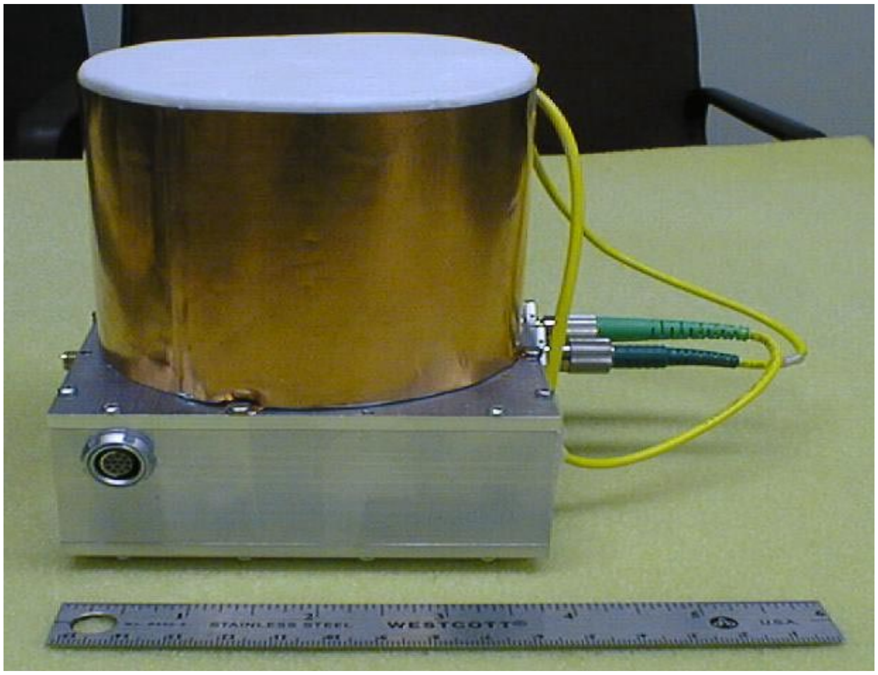


Fig. 2. An OEO module consisting of all devices shown in Fig. 1.

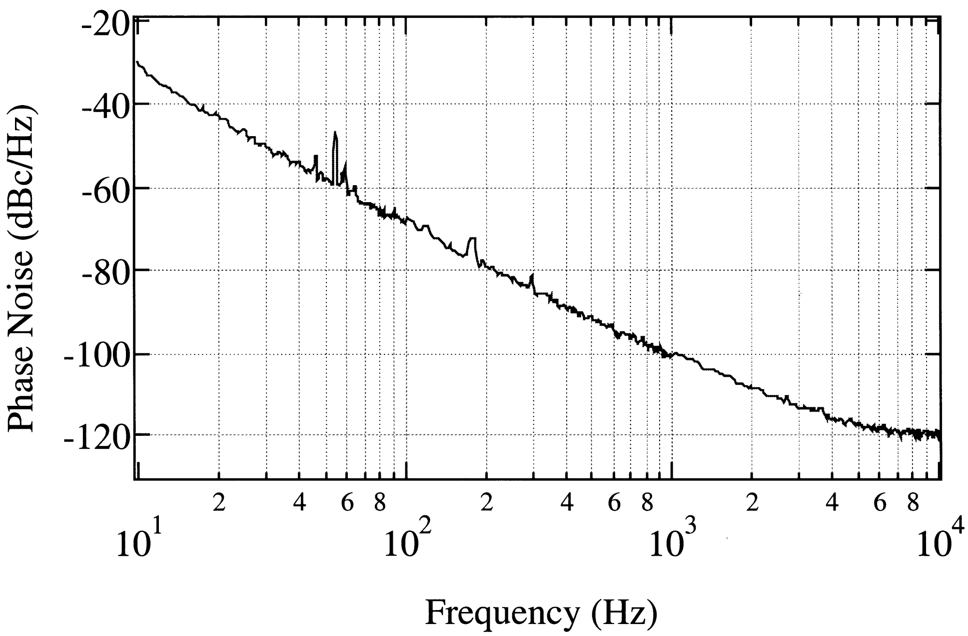
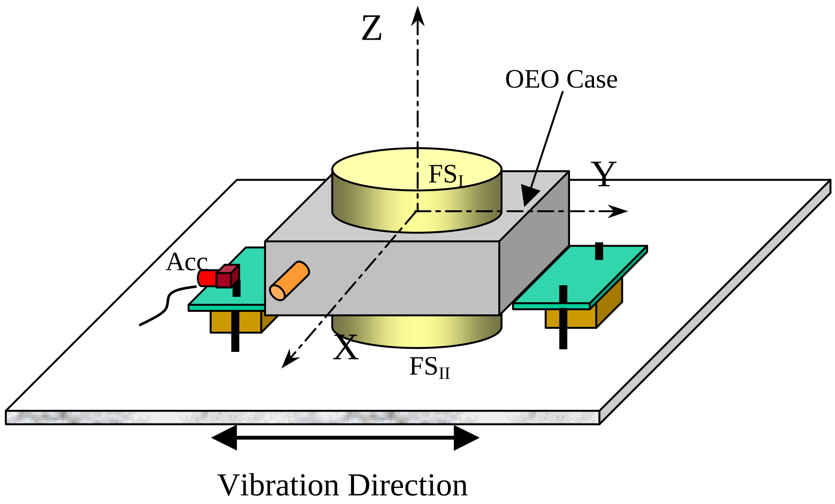
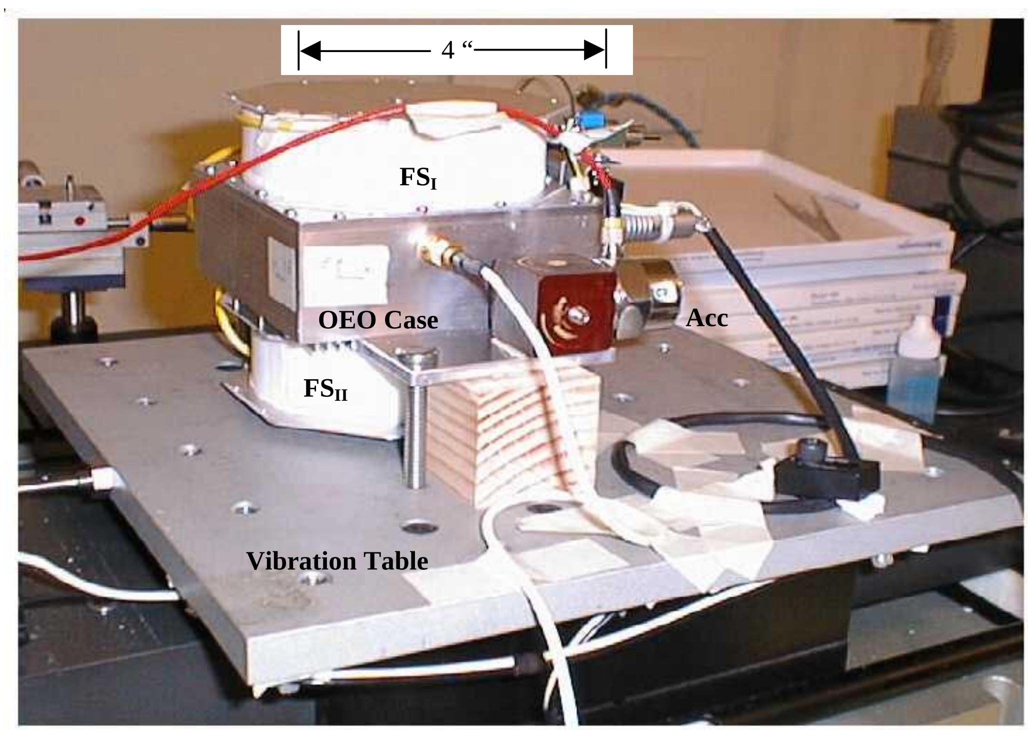


Fig. 3. Single side-band phase noise spectrum of the OEO module



(a) OEO vibration testing diagram



(b) OEO vibration testing setup

Fig. 4. OEO Vibration Testing Setup. FS$_I$: Fiber Spool I, FS$_{II}$: Fiber Spool II, Acc: Accelerometer.

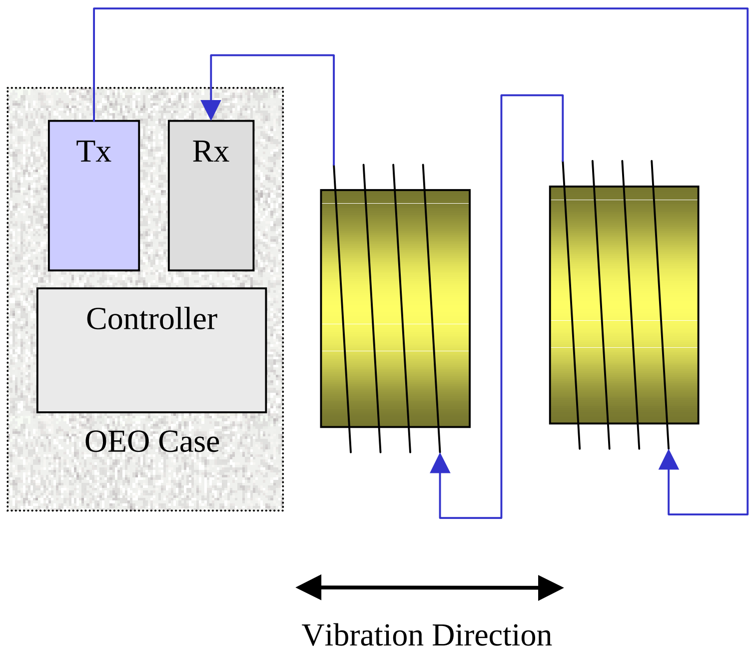


Fig. 5. Combined Spool OEO Configuration.

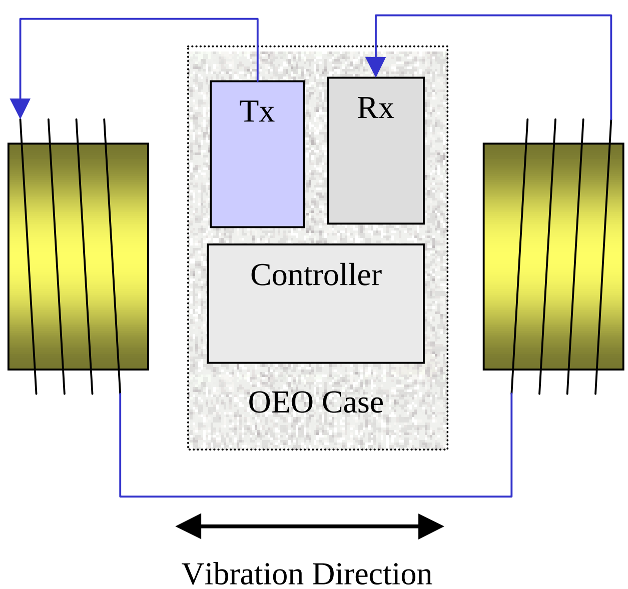


Fig. 6. Symmetric Connection Spool OEO Configuration.

Table 1. Vibration Test Results (without fiber delay line compensation)
OEO-2, Fc=11.763 GHz, Fv=40 Hz, Value in 10^{-10}/G

Number of Test	Γx	Γy	Γz	ΓT
1	0.713	0.650	32.259	32.273
2	0.465	0.900	32.146	32.162
3	0.453	1.124	30.870	30.894
4	0.584	0.982	31.484	31.505
5	0.556	0.485	33.886	33.894
Average	**0.554**	**0.828**	**32.129**	**32.144**

Table 2 Vibration Test Results (with fiber delay line compensation)
OEO_2, Fc=11.763 GHz, Fv=40Hz, Value in 10^{-10}/G

Number of Test	Γx	Γy	Γz	ΓT
1	0.713	0.650	0.970	1.368
2	0.465	0.900	1.140	1.525
3	0.453	1.124	0.460	1.296
4	0.584	0.982	0.820	1.406
5	0.556	0.485	0.740	1.045
Average	**0.554**	**0.828**	**0.826**	**1.294**

Table 3 Vibration Test Results (with fiber delay line compensation)
OEO_2, Fc=11.763 GHz, Fv=60Hz, Value in 10^{-10}/G

Number of Test	Γx	Γy	Γz	ΓT
1	0.587	0.813	1.310	1.650
2	0.791	0.477	1.400	1.677
3	1.008	0.419	0.940	1.441
4	0.629	0.497	1.230	1.468
5	0.657	0.702	0.740	1.213
Average	**0.734**	**0.582**	**1.124**	**1.463**