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IN-CHIP DEVICE-LAYER THERMAL ISOLATION OF MEMS RESONATOR FOR LOWER POWER BUDGET

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ABSTRACT

This paper presents a thermally isolated ovenized design of MEMS resonator. Ovenization (joule heating) is done to compensate for the temperature dependence of resonator frequency. An ovenized resonator has a stable frequency over a wide temperature range of -40°C to 85°C. However, the ovenized designs lead to power consumption because of joule heating. It is therefore necessary to thermally isolate the device in order to reduce the power consumption. In this paper, we demonstrate an in-chip thermal isolation and heat delivery within the device layer of the silicon resonator that reduces the power requirement without compromising on the overall performance of the device. A power consumption of 12mW for an ovenized MEMS resonator, built within a wafer-scale encapsulation process, is reported here.

INTRODUCTION

Resonators have their applications in timing/frequency references, communication systems, global positioning systems, sensors [1], etc. Silicon MEMS resonators have potential to replace quartz crystal resonators because of small size, low cost, CMOS compatibility and low power consumption. An ovenized quartz resonator can have a size of more than 1000 mm^3 and may consume power of up to 5 watts. However, the MEMS resonators exhibit high frequency dependence on temperature. An uncompensated stress free silicon resonator has a temperature coefficient of frequency (TCF) of approximately -30 ppm/°C, which is primarily due to material softening of silicon [2, 3]. Several temperature-compensation techniques have been explored [3-5], which enable frequency control over a wide temperature range of -40°C to 85°C. Active temperature compensation [4, 5] using joule heating has the potential to precisely control frequency within the stipulated industry or military standards. In this method, a device is held at a fixed temperature and a heating power is applied to compensate for the change in ambient temperature of the resonator. However, this heating is responsible for undesirable power consumption.

To minimize power consumption, a micromachined resonator needs to be thermally isolated to reduce the heat loss and at the same time there should be an efficient heat delivery mechanism. In this paper, we describe a resonator design which has an in-built heater directly attached to the resonator. The in-built heater locally increases the heating efficiency as well as the thermal isolation.

DESIGN DESCRIPTION

1. Ovenized resonator without thermal isolation

A double anchored, double ended tuning fork (DETF) type resonator design is shown in figure 1a. The Resonator beams are electro-statically actuated by providing AC stimulus signal to input electrodes. The beams are maintained at a constant bias voltage. Due to capacitive action between the beams and input electrodes, the resonator beams start vibrating. When the frequency of the input AC stimulus signal becomes equal to the natural frequency of the DETF structure, the beams start resonating at that frequency. The bias voltage can be adjusted to increase the amplitude of the resonance. The output signal is amplified to measure the resonant frequency.

The DETF is fabricated in the device layer of a silicon on insulator (SOI) wafer as shown in figure 1b. A wafer-scale encapsulation process [6-9] is used to fabricate the structure. This process ensures a close-to-vacuum environment inside the cavity within which the resonator operates. The device layer is separated by the thickness of a thin sacrificial oxide layer from both encapsulation cap at the top and substrate at the bottom (Figure 1b). The electrical contacts are made through the encapsulation over the anchors. An SEM

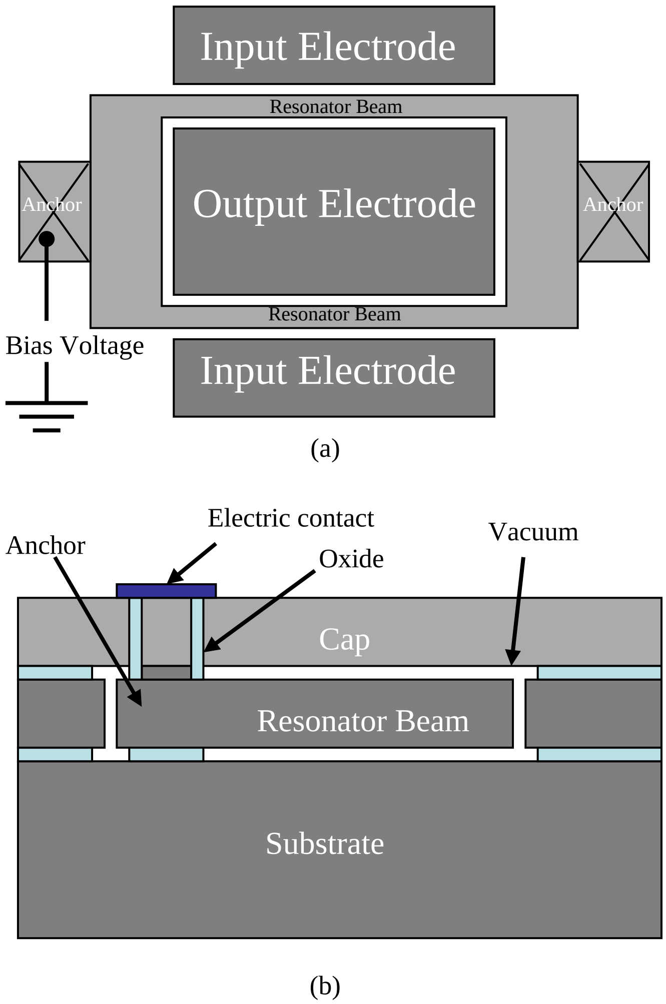


Figure 1: (a) Double anchored double ended tuning fork (DETF) type resonator structure. (b) A typical schematic of a die (chip) from an SOI wafer showing the details of encapsulated MEMS resonator. The resonator is in the device layer which is separated by the thickness of a sacrificial oxide from substrate at the bottom and encapsulation cap at the top.

cross-section view of a typical encapsulated DETF is shown in figure 2.

In an ovenized MEMS resonator, temperature control is done to get stable frequency output. Temperature is controlled by sensing the temperature of the resonator and then heating it back to set-temperature using a feedback control loop [4, 5]. The resonator is always maintained at a constant temperature irrespective of the changes in ambient temperature. The set point is selected as the maximum operating temperature of the device. The extent to which resonator is heated is dependent on the difference of the set point and the ambient temperature. Hence, maximum heating is required when the ambient temperature is at the lowest.

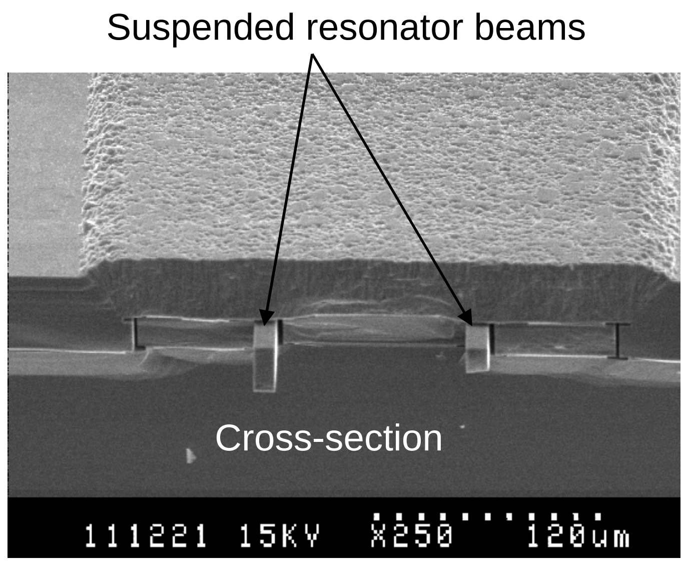


Figure 2: SEM view of encapsulated resonator beams

For an ovenized resonator stipulated to operate within a temperature range of -40°C to 85°C, the heating has to cover the range of 125°C.

Our conventional resonators which do not contain in-built thermal isolating mechanisms have exhibited a power consumption of around 100 mW to 200 mW, depending upon the design and packaging, for a temperature range of 125°C.

An in-built thermally isolated design contains an in-built-heater which is directly coupled with the resonator. This heater is used simultaneously for both joule-heating as well as thermal isolation. The resonator is placed as close to the heater as possible for maximum heating and at the same time provide high thermal resistance in the path of heat loss from the resonator to the ambient.

2. Heater design theory

To design a resonator for good thermal isolation, it is necessary to study various heat loss mechanisms in the structure. The total effective thermal resistance due to substrate, encapsulation cap, bonded wires, etc at each anchor of the DETF structure is estimated to be approximately 2500 K/W. The resonator is encapsulated and is in vacuum environment. The pressure inside the cavity is in the range of 0.0035mbar [10]. Hence it can be assumed that the heat loss due to convection is negligible. The thermal resistance due to radiation for a DETF structure is estimated to be approximately 1×10^6 K/W. Hence for simplification, it is also assumed that the heat loss due to radiation is relatively small and can be neglected.

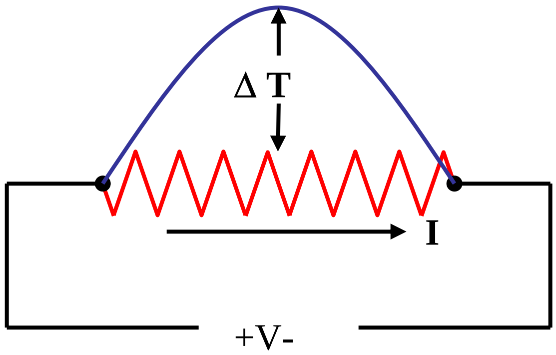


Figure 3: Temperature profile along the length of a resistive heater when a current is passed through it. The rise in temperature is proportional to the joule heat, q generated in the resistor and its effective thermal resistance.

It is, therefore, the conductive heat transfer which plays the dominant heat loss mechanism in micro-machined parts.

When electric current is applied along the length of the resistive heater, its temperature profile is parabolic as shown in the figure 3. The temperature distribution across the length of heat generating solid is given by equation (1).

$$T_x = \left(\frac{q' l^2}{8k}\right)\left(1 - \frac{4x^2}{l^2}\right) + T_s \qquad (1)$$

Where q' is the heat energy generated per unit volume, l is the length, k is the thermal conductivity of the solid, T_s is the temperature of the end surface.

The maximum temperature occurs at the center of the heater and is given by equation (2).

$$T_c = \left(\frac{q' l^2}{8k}\right) + T_s \qquad (2)$$

The rise in temperature at the center of the heater with respect to its end surface is given by equation (3) and is directly proportional to the total joule heat generated in the resistor and the thermal resistance of the heater.

$$\Delta T = \frac{q' l^2}{8k} = \left(\frac{V^2}{R_e}\right)\left(\frac{R_{th}}{8}\right) = q.R' \qquad (3)$$

Where $R_{th} = \dfrac{l}{kA}$

$$q' = \frac{q}{lA} = \frac{\left(\frac{V^2}{R_e}\right)}{lA}$$

q is the total heat generated, V is the applied voltage, R_e is the electrical resistance, A is the cross section area. From (3) we can establish an equivalence between a current carrying beam having thermal resistance of R_{th} and heat generation of q with a lumped model having thermal resistance of R' and heat flow of q for the same rise in temperature, where R' is eight times smaller than R_{th}. This shows that, to get maximum temperature rise in the resonator beam for a given input power, the thermal resistance of the heater should be as large as possible and at the same time it is desirable to have smaller electrical resistance of the heater. Thermal resistance directly depends on the length of the beam and inversely proportional to cross-section area. Design of large thermal resistance is constrained by the reduction of mechanical stiffness of the structure. However, miniature design of the resonator and heater allows for relatively higher thermal resistance.

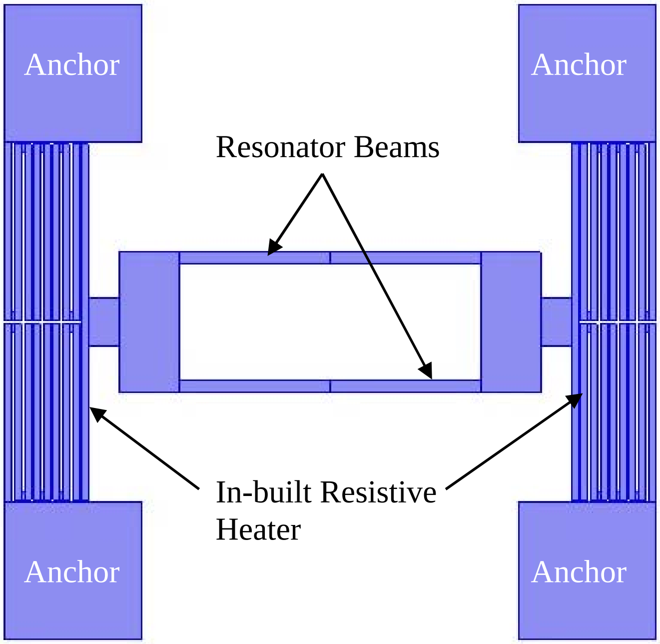
3. Ovenized resonator with thermal isolation

Thermally isolated DETF type resonator is shown in figure 4a. An in-built resistive heater is used to provide thermal isolation on both sides of the resonant structure. Heating can be done on either side of the structure. The cross-section of the heater beam is 5 micron by 20 micron and its total length is around 2300 micron. The resonator is attached at the center of the heater (figure 4b) for maximum heating. The entire structure is released except at the four anchors which act as mechanical supports at the bottom and provide electrical contacts at the top. The anchors are electrically insulated by oxide. The thermal resistance of the in-built heater is approximately 150,000 K/W.

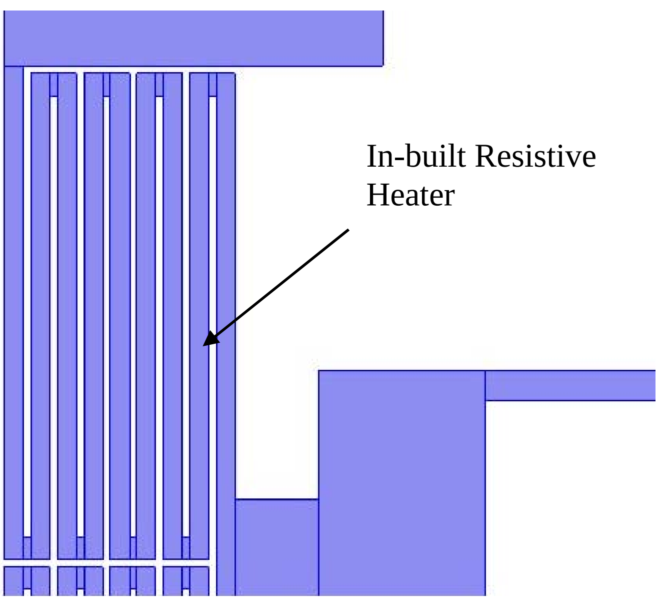
Voltages V_1 and V_2 are applied to heat the resonator as shown in figure 5. The potential difference between V_1 and V_2 acts as a joule heating voltage V_h across the in-built heater.

$$V_1 = V_b + \frac{V_h}{2}$$

$$V_2 = V_b - \frac{V_h}{2}$$



(a)



(b)

Figure 4: Thermally isolated (ovenized) DETF structure design with in-built resistive heater directly coupled with the beam in the device layer. The entire structure is designed to be released except at the anchors where it is connected with the substrate and the cap through oxide. (a) Top view of the DETF, (b) Enlarged view of the heater

The bias can be measured at the other end of DETF structure (figure 5). The resonator should see a constant bias voltage of

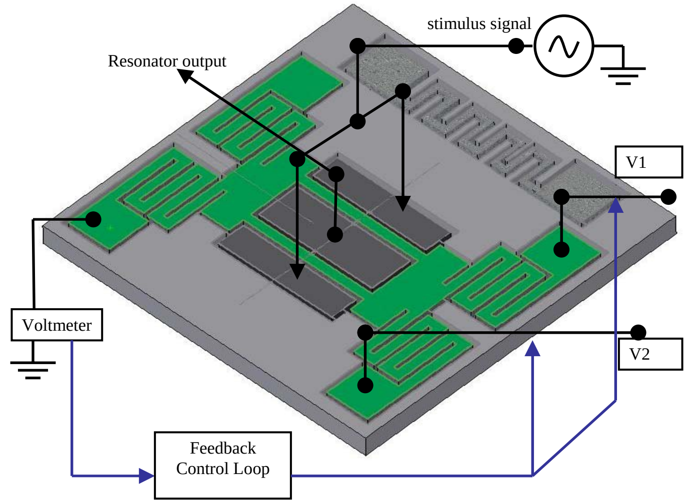


Figure 5: A schematic of the device layer containing DETF with in-built heater. As shown the stimulus signal is simultaneously applied to the two input electrodes with the centre electrode acting as an output. V1 and V2 are the heating voltages and are controlled using feedback control loop to maintain the bias of the resonator at a constant level.

V_b , because of symmetric design. However, fabrication uncertainties result in asymmetry of the heaters that causes the bias voltage to change. Change in bias causes the change in frequency. This introduces an error into the frequency measurement which is later used to estimate the temperature of the resonator. In order to remove the effect of change in bias voltage, a feedback control loop (figure 5) is implemented to maintain a constant bias within 1mV precision.

ESTIMATION OF POWER CONSUMPTION

A one dimensional equivalent-resistance analytical model has been used to estimate the temperature of the resonator. It is assumed that the center of the heater is at maximum temperature and the entire resonant structure (DETF) sees the same maximum temperature. This assumption will lead to an upper-bound of the temperature estimation at a given input power. The total effective thermal resistance from the centre of the heater to the ambient is estimated to be approximately 13000 K/W (figure 6).

A finite element simulation has been done to examine the temperature distribution along the heater length (figure 7). A comparison between 1-D analytical and FEM results is shown in figure 8.

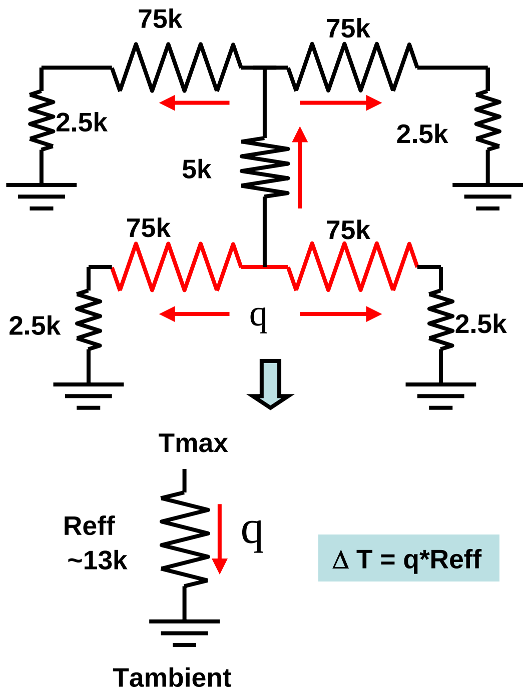


Figure 6: 1-D equivalent-thermal-resistor network of heat loss paths in DETF. The heater has 75000 K/W of thermal resistances on both sides of its center. The effective thermal resistance of the resonator beam is 5000 K/W. Thermal resistance of 2500 K/W is due to substrate, encapsulation cap, bonding wires, etc. The total effective thermal resistance between the resonator and the ambient is estimated to be 13000 K/W.

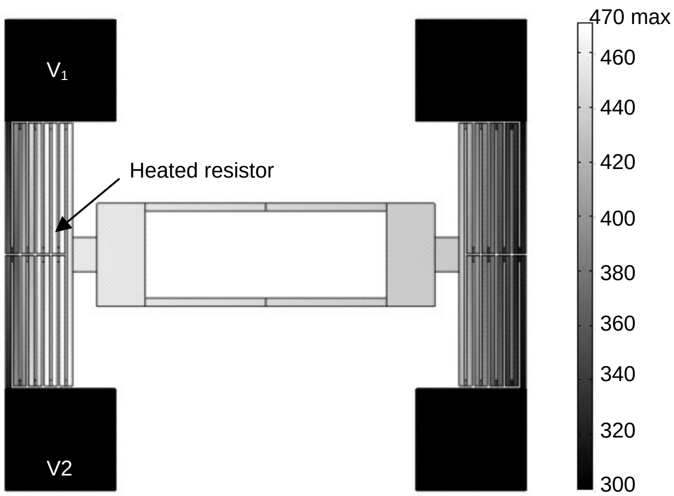


Figure 7: Finite element simulation of the thermally isolated DETF resonator showing the temperature distribution in Kelvin.

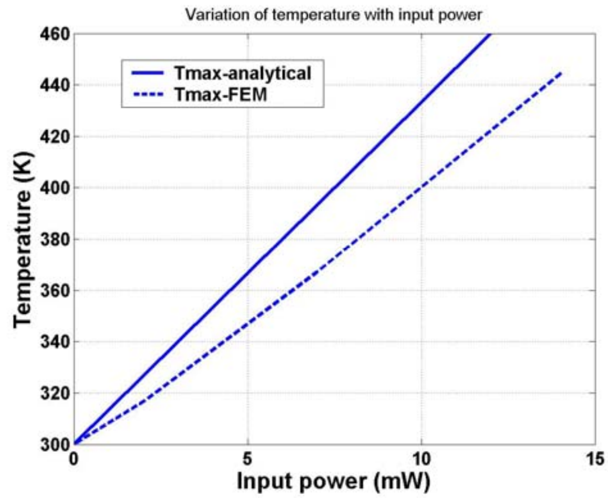


Figure 8: Comparison of analytical and FEM results.

EXPERIMENTAL RESULTS

A 1.3 MHz resonator was used for the experiment. It was first calibrated by measuring its frequency in an oven at different temperatures. The measured temperature coefficient of frequency (TCF) was found to be constant and equal to -29 ppm/°C (figure 9) which is same as stress free single-anchored resonator beam.

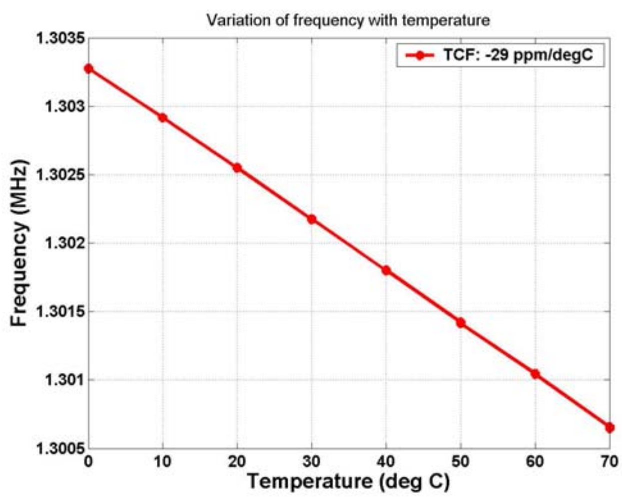


Figure 9: The device was pre-calibrated with oven temperature and that the variation of frequency with temperature (TCF) was measured to be -29ppm/°C.

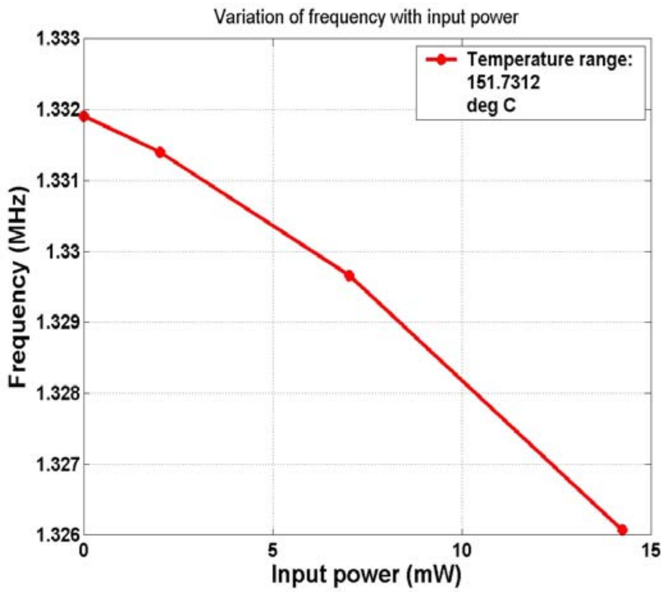


Figure 10: The effect of heating power on frequency is measured. The change in temperature was estimated by measuring the change in frequency.

With this calibration data it is possible to use frequency as temperature sensor. The device is then heated by applying voltage across the in-built heater and its frequency is measured at different input powers. As shown in figure 10, the frequency decreases with the increase in input power and the change in frequency is due to the rise in temperature of the resonator caused by joule heating of the resistor.

It shows that there is a rise in temperature of 125°C with total power consumption of 12 mW. The experimental result is compared with the analytical and FEM simulation output. The experimental data matches within 8% of the estimated value (Figure 11).

CONCLUSIONS

In this work, we demonstrated that MEMS resonators can be simultaneously heated as well as thermally isolated by designing a heater coupled with the resonator in the device layer of the die (chip). The heater serves dual purpose of localized efficient heating as well as miniaturized thermal isolation in the device layer and hence provides maximum heating with reduced input power. Furthermore, this design does not require any change in fabrication process of resonator because the resistive heater is placed in the same layer as that of resonator and the entire device layer is fabricated simultaneously. At the same time the device has high resistance to shock because of its miniature design.

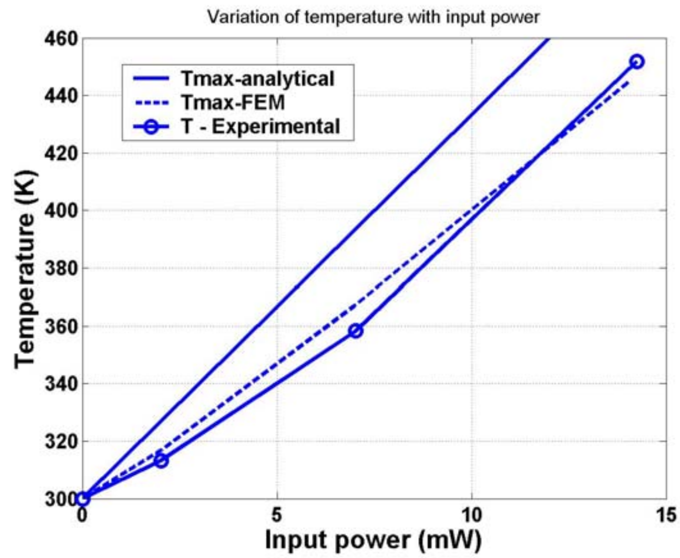


Figure 11: This plot compares the result from analytical, FEM and experimental data. The resonator temperature increases by around 125 °C at an input power of 12 mW. The analytical result gives an upper bound because of the assumption made in the calculation.

FUTURE WORK

It is possible to design an optimum heater coupled resonator which can further maximize the heating as well as thermal isolation and at the same time maintain its mechanical stiffness and temperature uniformity. In future we plan to achieve even lower target of 5mW for a temperature range of 125°C by further investigation and design optimization.

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