A MEMS RF PHASE AND FREQUENCY MODULATOR

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ABSTRACT

We present a method to create a RF MEMS oscillator with continuous control of the output phase and frequency. When the weakly nonlinear oscillating system becomes synchronized with an imposed sinusoidal force of close frequency, the resonator frequency can be detuned with a DC bias on a resistive actuator to produce an easily controlled phase differential between the injected signal and the resonator feedback. We demonstrate a 26 MHz MEMS oscillator with frequency tunability of 0.3% and phase tunability of 200˚. By modulating the Joule heat dissipated in the structure, a 26 MHz carrier frequency was either frequency modulated by a 30 kHz baseband signal with a modulation depth of 15 kHz, or phase modulated by a 20 kHz baseband signal with a modulation depth of 160˚.

Keywords: Voltage Controlled Oscillator, Entrainment, Phase Modulation, RF MEMS

INTRODUCTION

Frequency sources that are tunable in frequency and phase are essential parts in modern communication and radar applications. Phased-array radar systems rely on high frequency field-effect transistor switches and networks of delay lines that offer the ability to individually tune the phase of a common RF source in discrete increments. Recently, n-bit networks of radio frequency (RF) microelectromechanical (MEMS) capacitive switches have shown promise to replace the active components found in these phased-arrays [1], [2]. Such mechanical devices offer significant advantages in terms of power consumption and insertion loss over conventional solid-state phase shifters but are limited by their discrete nature and relatively large size. In this paper we present a method of using a RF MEMS frequency source capable of producing continuous variations in phase, thus eliminating the need for delay line networks. By controlling the DC bias of a self-generating, injection-locked, thermally actuated micromechanical resonator we are able to continuously vary the frequency and phase of the output signal. An array of such micron-sized tunable oscillators would be a compact method for implementing beam steering or beam formation in a phased-array antenna. The ability to produce continuous frequency or phase variations also shows promise for applications in wireless communications, where information is encoded in phase or frequency modulated signals. By modulating the DC bias with a baseband signal, the MEMS oscillator can generate a wide bandwidth phase or frequency modulated carrier frequency.

METHODS

The micromechanical resonator (Fig. 1) used in the study is a 30 μm diameter polysilicon shell type resonator with resonant modes between 10 and 30 MHz and a mechanical quality factor of ~10,000. The shell resonator is a circular, 200 nm thick plate, clamped on the periphery and suspended via removal of the sacrificial oxide in the center (Fig. 2). Due to compressive stress in the polysilicon film, the circular plate has a convex or concave dome-like curvature, enhancing the resonant frequency of the device and providing a means of thermal actuation [3]. The input transducer of the micromechanical resonator is a 50 Ω gold resistor, lithographically defined on the surface of the dome, which couples Joule heat to mechanical stress in the shell, inducing out-of-plane displacement. The

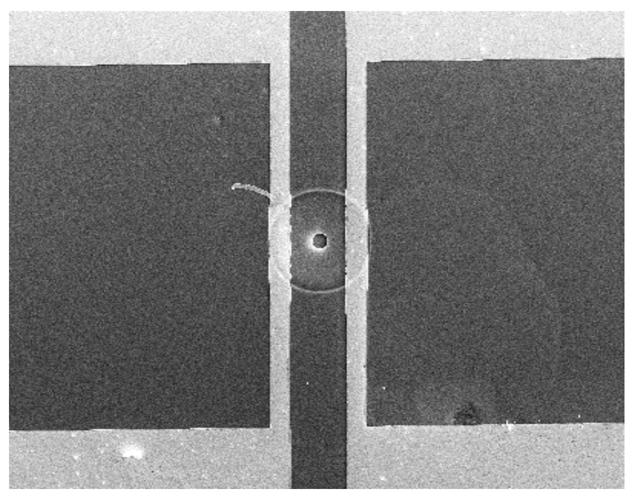

Fig. 1. SEM image of the dome resonator and actuator. Circular charged ring shows the lateral dimension of the 30 μm diameter shell-type resonator. Two gold resistors are defined vertically along the periphery of the resonator, forming two electrically isolated actuators.

Fig. 2. Bisection of the polysilcon shell-type micromechanical resonator.

dome resonates when the frequency of the current flowing through the microheater matches a resonant mode of the structure. The driving force provided by the thermal actuator is described by (1)

$$F_{\omega_o} \propto \Delta T \propto V_{RF}^2 \big/ R \propto V_{DC} V_o \sin(\omega_o t) / R\,, \qquad (1)$$

where ΔT is the local change in temperature and R is the resistance of the actuator. The small thermal time constant of the thin film resonator allows the local temperature to be modulated and the heat dissipated at a rate comparable to the time constant of mechanical motion at resonance allowing driven resonance and high modulation rates. The resulting motion is detected with a HeNe laser using the resonator and sacrificial oxide cavity as a Fabry-Perot interferometer [4]. All experiments were conducted in a custom vacuum chamber at $1\text{x}10^{-7}$ Torr to reduce viscous damping loss; however, operation at ambient pressures has been achieved with a Q of ~100. Two resistors connected to independent bonding pads can be defined on the resonator, allowing the possibility of multiple electrically isolated resonator transducers. For two resistors spaced about 20 µm apart, –50dB of electrical crosstalk was measured.

By applying the laser detected displacement signal as feedback onto the input transducer, the micromechanical dome resonator can function as a stable frequency source. Fig. 3 shows a schematic for this mode of operation. The photodetector signal, representing the mechanical motion of the resonator, is first amplified by about 50dB, depending on the intensity of the detection

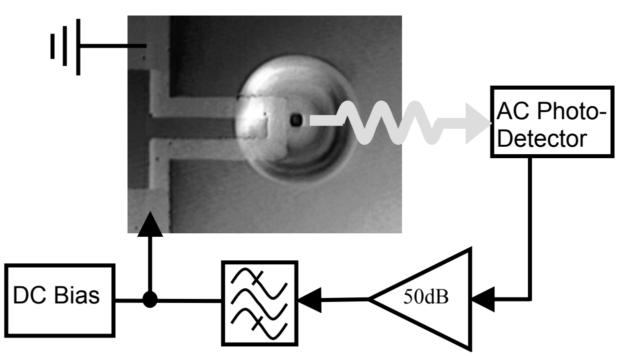

Fig. 3. Feedback network of the dome oscillator

laser. To select the resonator mode of vibration and to provide adjustable in-loop phase, the feedback signal is filtered by a low-Q band pass element. A DC bias less than 1 V is superimposed on the feedback signal and subsequently applied to the driving resistor. Limit-cycle oscillations at the free-running frequency, f_{FR}, will grow out of the unstable equilibrium point of the system when the feedback network is tuned to provide a gain greater than 1 with a phase shift of an integer multiple of 2π. The amplitude of the oscillations is limited by the nonlinearity of either the mechanical resonator or the amplifier. A frequency generator with short-term stability of 1.5 ppm has been achieved with this setup [5].

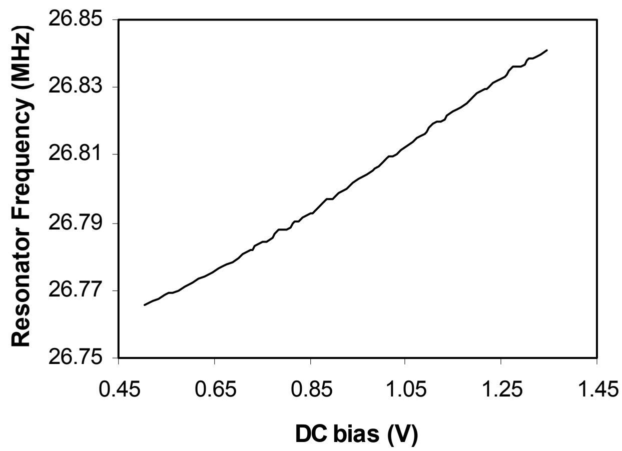

Fig. 4. Frequency tuning of a dome oscillator (feedback amplitude = 380mV). One resistor is used to close the feedback loop while a 2nd resistor alters stress in the shell through an applied DC bias, changing f_o.

The resonant frequency, f_o, of the dome and thus, f_{FR} of the oscillator, can be easily tuned by changing the amount of heat dissipated into the polysilicon film. Steady-state heat, imposed either by the HeNe detection laser or by a DC bias on the thermal actuator, will cause a change in resonator stiffness due to thermal expansion in the film, changing the natural frequency of the shell resonator (Fig. 4). Depending on the location of the heat source and the sensitivity of the effective spring constant of a shell resonant mode to thermal expansion, a frequency deviation of 0.35% over a 1V change in DC bias can be achieved.

It is well known that a weakly non-linear self-oscillatory system can be synchronized to a periodic force superimposed on the system, provided that the natural frequency and the perturbation frequency are not far different [6]. Previous research by Zalalutdinov et. al. [7] demonstrated that limit cycle oscillations (in the absence of external forcing) in a micromechanical resonator could be locked in frequency and phase to a small perturbation or pilot signal, f_{pilot}, which was superimposed on the resonator via a modulated laser. In this work we demonstrate injection locking of the MEMS oscillator with a thermally induced pilot signal applied with the electric heater. A map showing the regions of capture and loss of entrainment of the dome oscillator is shown in Fig. 5. To create this plot, positive feedback is applied to one resistor, causing self-generation at frequency f_{FR}. A pilot signal, used to entrain the oscillator, is then applied to a second resistor on a completely isolated signal path. The pilot signal is swept in frequency to establish the region where the mechanical oscillator is entrained. Within the region of entrainment, the resonator oscillations take on the frequency stability of the pilot signal. Hysteresis can be seen between the points where lock is lost (the pull out frequency) on the upward pilot sweep and where lock in resumed on the downward sweep. The perturbation is then incremented in amplitude, which serves to broaden the entrainment region.

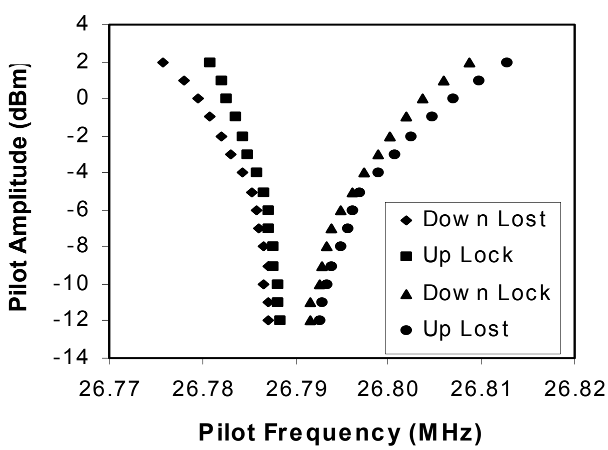

Fig. 5. Region of entrainment of a self-generating mechanical oscillator (feedback = 380mV RMS, pilot DC bias = 700mV). Hysteresis is shown between the upward and downward sweeps of the pilot signal.

Phase tuning of a reference signal has been previously demonstrated in analog circuits through entrainment of a LCR oscillator [8]. By detuning a pilot signal superimposed on a tank circuit away from the unperturbed resonant frequency of the tank, a phase difference is produced between the tank feedback and the pilot signal that is related to the difference between f_o and f_{pilot}. Phase lag in the entrained MEMS resonator is similarly induced by detuning the fundamental frequency of the resonator, f_o, with a DC bias. Changing f_o moves the entrainment "V" relative to the pilot signal instead of the opposite situation that was used to measure the entrainment map. To maintain frequency synchronization, the phase of the mechanical vibrations changes according to the phase-frequency function of the resonator. This phase change can be measured between the pilot signal and the self-generation feedback signal. Thus, a phase difference can be obtained by simply changing the magnitude of the voltage impressed on the oscillator rather than requiring a complex method of changing the pilot signal frequency. Furthermore, by changing f_o and not f_{pilot}, the output phase can be tuned while f_{FR} remains unchanged. Fig. 6 demonstrates that the total phase shift between f_{FR} and f_{pilot} can be controlled by as much as 200°. Beyond this region of DC bias tuning, the region of the entrainment V is shifted to the extent that the oscillator will lose the lock on the pilot signal, and the entrained condition required to produce the phase differential will collapse, producing quasiperiodic motion.

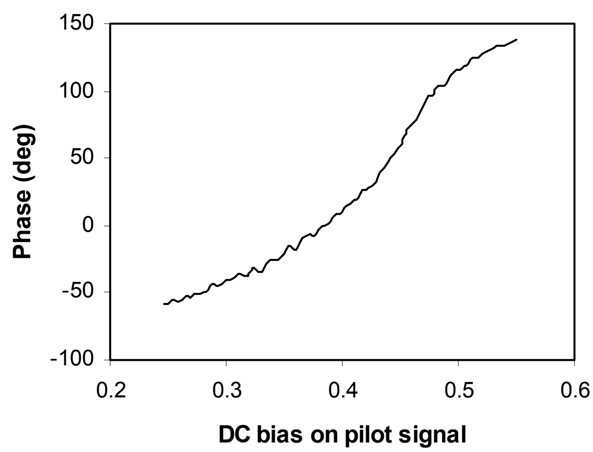

Fig. 6. Phase difference between f_{FR} and f_{pilot} in an entrained oscillator as f_o is detuned by DC bias (feedback = 380mV RMS, pilot = -10dBm, $f_{pilot} = f_{FR}$ =26.79 MHz)

Besides the potential for delay line applications, the entrained oscillator can also produce a phase or frequency modulated carrier signal for use in communication systems. In the simplest case, frequency modulation of the oscillators' free running frequency can be achieved by applying a baseband AC signal that will perturb the resonators fundamental frequency. The low-frequency bias causes f_o to change, creating a carrier frequency, f_{FR}, which is modulated at the rate of the baseband signal on the resistor. The depth of the modulation superimposed on the carrier is defined by the Hz/Volt transfer function of the resistive actuator and resonator mode. To eliminate adder circuitry and achieve better isolation between the baseband signal and the carrier signal, the baseband signal can be applied to a second resistive actuator. Using this setup, frequency modulation of a 26 MHz carrier by a 30 kHz baseband signal was demonstrated with a modulation depth of 15

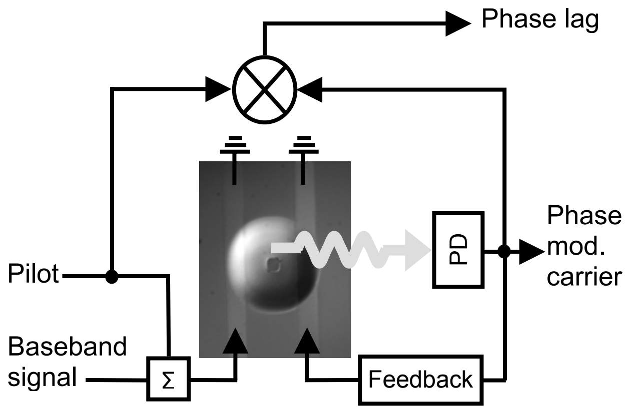

Fig. 7. Setup for MEMS phase shifter and modulator. Right resistor is used in the feedback loop and left resistor is used for the pilot signal and baseband signal.

kHz. A spectrum analyzer with a high video bandwidth, centered on the carrier frequency, was used to demodulate the carrier.

Phase modulation is demonstrated by superimposing a baseband AC signal onto the pilot resistor while the resonator is self-generating and entrained by the pilot signal. Fig. 7 demonstrates the experimental schematic. The right microheater applies positive feedback from the photodiode while the left microheater is used to entrain the resonator with the pilot as well as supply an AC baseband signal. The time varying baseband signal, through the additional heat dissipated in the resistive actuator, pulls the natural mechanical frequency across the pilot frequency. Detuning the resonator causes a time varying phase difference between the pilot signal and the feedback signal that is proportional to the time varying baseband amplitude. The phase modulated carrier signal can be sampled from the oscillator feedback with an I/Q demodulator. Phase modulation of a 26 MHz carrier by a 20 kHz baseband signal was demonstrated with a modulation depth of 160˚.

CONCLUSION

Using the non-linear dynamics of a micron-sized mechanical oscillator, we have demonstrated a frequency source with the ability to tune the phase and frequency of the output signal. By controlling the DC bias supplied to the resonator through a thermal actuator, the resonant frequency of the device can be changed, allowing the control (depending on the implementation) of continuous phase or frequency shifts in the output signal. We demonstrate a 26 MHz MEMS oscillator with frequency tunability of 0.3% and phase tunability of 200˚. An array of similar resonators could all be locked to a single, highly stable, frequency source (common in the HF or VHF frequency range) and individually detuned with a separate signal. Upconversion to the EHF frequency range for radar applications would be possible using a single source following the mechanical phase tuning stage.

Silicon based MEMS tunable oscillators would also provide an alternative to discrete components in communication architectures such as quartz crystal frequency sources or voltage controlled oscillators. We demonstrate a 26 MHz oscillator with FM modulation of 30 kHz and PM modulation 20 kHz. A high *Q*, tunable frequency source, which could be readily incorporated into standard integrated circuit fabrication processes, is a critical step toward the realization of integrated radio-on-chip communication systems.

Acknowledgments

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