



Equivalent-circuit modeling of a MEMS phase detector for phase-locked loop applications



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ABSTRACT

This paper presents an equivalent-circuit model of a MEMS phase detector and deals with its application in phase-locked loops (PLLs). Due to the dc voltage output of the MEMS phase detector, the low-pass filter which is essential in a conventional PLL can be omitted. Thus, the layout area can be miniaturized and the consumed power can be saved. The signal transmission inside the phase detector is realized in circuit model by waveguide modules while the electric-thermal-electric conversion is illustrated in circuit term based on analogies between thermal and electrical variables. Losses are taken into consideration in the modeling. Measurement verifications for the phase detector model are conducted at different input powers 11, 14 and 17 dBm at 10 GHz. The maximum discrepancies between the simulated and measured results are 0.14, 0.42 and 1.13 mV, respectively. A new structure of PLL is constructed by connecting the presented model directly to a VCO module in the simulation platform. It allows to model the transient behaviors of the PLL at both locked and out of lock conditions. The VCO output frequency is revealed to be synchronized with the reference frequency within the hold range. All the modeling and simulation are performed in Advanced Design System (ADS) software.

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1. Introduction

Phase-lock loop (PLL) is a technique which has found applications in wireless communication systems, high speed digital circuits and instrumentations [1,2]. A classical PLL is configured by three major functional units: a phase detector, a low-pass filter (LPF) and a voltage-controlled oscillator (VCO). Present trend of PLL is moving towards MEMS technology for miniaturization and performance improvement [3]. The potential and feasibility of MEMS-based oscillators in PLL have been investigated for many years due to their high quality factors and wide tuning ranges [4–6]. However, the LPF is still the main reason for the limitations of a completely miniaturized and energy-efficient PLL.

According to our previous studies [7,8], the output of a MEMS phase detector is dc voltage which can act directly as the control voltage of the VCO. Consequently, the LPF can be omitted with layout area and power saved. However, the application of MEMS phase detector in the context of a PLL has not been investigated previously. A MEMS phase detector involves complicated processes including signal transmission and electric-thermal-electric conversion. Nevertheless, in the concept of integrate circuit design for a PLL based on MEMS phase detector, such a high level of physical specialization is not needed. Instead, it is essential to utilize an

equivalent-circuit model as a design and verification tool due to its simplification and rapid solving process.

For these reasons, this work addresses the equivalent-circuit modeling of a MEMS phase detector and studies its application in PLL. Section 2 gives the mathematic analysis of the MEMS phase detector and the corresponding PLL. The heat transfer problem inside the phase detector is analyzed in spherical coordinate which is easy to be implemented in circuit design. The signal transmission and electric-thermal-electric conversion are illustrated in circuit terms in Advanced Design System (ADS) in Section 3. Losses are taken into consideration in the modeling. The integrated equivalent-circuit model for the MEMS phase detector is established, simulated and verified effective by measurement. A new PLL structure without any filters is constructed by connecting the proposed phase detector model to a VCO module. Transient responses of the PLL are simulated both at locked and out of lock conditions. The VCO output frequency is revealed to be synchronized with the reference frequency within the hold range. It has shown that the equivalent-circuit model of the MEMS phase detector should be able to support the application in PLL.

2. Mathematical analysis

Fig. 1a presents the function block diagram of a conventional PLL composed of a phase detector, a low-pass filter (LPF) and a voltage-controlled oscillator (VCO). As is illustrated, the phase

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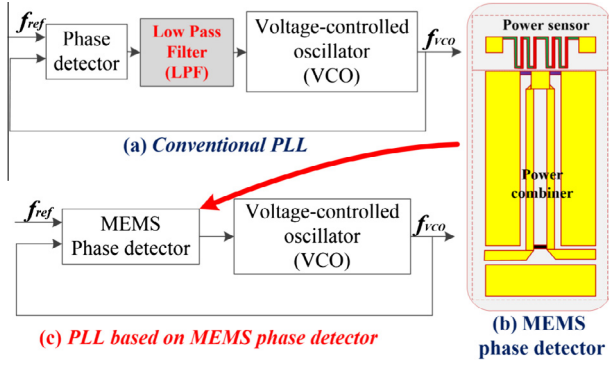


Fig. 1. (a) Function block of a conventional PLL, (b) schematic diagram of a MEMS phase detector and (c) function block of a PLL based on MEMS phase detector.

detector compares the phases of the two input signals (the reference signal and the VCO feedback signal) and delivers a voltage, which is a reflection of the phase difference, to the LPF.

Fig. 1b depicts the schematic diagram of a MEMS phase detector. It is configured with a power combiner and a thermoelectric power sensor [9]. The signals are injected into the phase detector through the two input ports of the power combiner. The thermoelectric power sensor is used to measure the combined power and generate a dc voltage, which is proportional to the phase difference between the two input signals. Substituting this MEMS phase detector into the closed-loop of the conventional PLL, a new architecture is obtained as shown in Fig. 1c. The LPF is omitted due to the dc output of the MEMS phase detector. The detailed mathematic analysis is given as follows.

Defining v_i and v_o as, respectively, the reference signal and the VCO feedback signal, which can be expressed as

$$v_i = V_i \cos(\omega_i t + \phi_i) \quad (1)$$

$$v_o = V_o \cos(\omega_o t + \phi_o) \quad (2)$$

where V_i and V_o are the amplitudes of the reference signal and the VCO feedback signal, ω_i and ω_o are their angular frequencies, and ϕ_i and ϕ_o are their initial phase constants, respectively.

The power combiner inside the MEMS phase detector is composed of input/output ports and transmission lines. It performs a vector combination [10] function to the input signals. Consequently, the power P of the combined signal is determined by the amplitudes of the input signals and the phase difference between them.

$$P = \frac{V_i^2 + V_o^2 + 2V_i V_o \cos((\omega_i - \omega_o)t + \phi_i - \phi_o)}{2Z_0} \quad (3)$$

The thermoelectric power sensor is cascaded subsequently to the power combiner. It contains a section of CPW, two load resistors, two output pads and a thermopile which is established by two different materials connected alternately in series. The CPW feeds the combined signal to the thermoelectric power sensor. The load resistors act as absorbing media to convert the energy of the combined signal into heat. As the heat transfers, temperature gradient will be established along the thermopile. The hot junctions of the thermopile are near, while the cold junctions are far away from, the load resistors. The temperature difference between the hot and cold junctions of the two different materials in the thermopile will result in a dc voltage at the output pads, which is known as Seebeck effect [11].

The heat transfer equation in the thermoelectric power sensor can be expressed by the following formula in spherical coordinate.

$$\Phi = -\lambda A \frac{dT}{dr} \quad (4)$$

where Φ is the heat flow converted from the combined power, λ is the thermal conductivity of the substrate, A represents the isothermal surface area along the heat flow path and r is the heat transfer distance. For case of steady-state heat transfer problem, the temperature gradient and the heat do not vary with time. Hence, the variables can be integrated as

$$T(r) = -\Phi \int_r^{240} \frac{1}{\lambda A(r)} dr + T_0 \quad (5)$$

where T_0 is the ambient temperature, and the integral part represents the thermal resistance R_{th} of the thermoelectric power sensor. Therefore, the temperature can be determined once the heat transfer distance is given.

According to the Seebeck effect introduced above, the dc voltage produced at the output pads of the phase detector can be expressed by the following equation. It is proportional to the Seebeck coefficients and the total temperature difference between each hot and cold junction.

$$V_{out} = (\alpha_1 - \alpha_2) \sum_{i=1}^N (T_h - T_c) \quad (6)$$

where α_1 and α_2 are the Seebeck coefficients of the two materials, T_h and T_c are the temperatures of each hot and cold junction, N is the number of thermocouples. Hence, the function of the MEMS phase detector is accomplished by transferring the phase difference into a variation of dc voltage. As is illustrated in Fig. 1c, this dc voltage is employed as the control voltage of the VCO in the new PLL structure.

The VCO instant angular frequency ω_{ins} reveals a linear function with the control voltage around the central angular frequency ω_o . With K_v representing sensitivity of the VCO and R_{th-e} symbolizing the total equivalent thermal resistance of the thermoelectric power sensor, the instant angular frequency of VCO is given by

$$\omega_{ins} = K_v R_{th-e} \frac{V_i^2 + V_o^2 + 2V_i V_o \cos(\Delta\phi)}{2Z_0} + \omega_o \quad (7)$$

$$\Delta\phi = (\omega_i - \omega_o)t + \phi_i - \phi_o \quad (8)$$

It is clearly shown that the instant angular frequency of the VCO changes linearly with the control voltage, namely the output voltage of the MEMS phase detector. The control voltage and the VCO instant frequency cannot become stable and the loop keeps unlocked until ω_o is synchronized with ω_i .

3. Modeling and verification

The SEM photograph of the fabricated MEMS phase detector is presented in Fig. 2. Its structure parameters are listed in Table 1. The fabrication processes are similar to our previous work [8] and are described briefly as follows. First of all, the fabrication starts on a GaAs wafer. The thermopiles are fabricated by an epitaxial layer of n+GaAs and a sputtered Au layer. The resistors are fabricated by a lift-off process after depositing a TaN layer. The power combiner is made by firstly evaporating an Au layer,

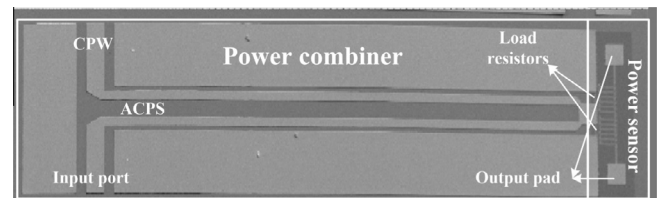


Fig. 2. SEM photograph of the MEMS phase detector.

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