Properties of metallic microwave-scale Mach-Zehnder interferometers for dielectric resonator tuning

H.J. De Los Santos, Y. Chen and C. Rusch

Modulation of the properties of metallic microwave-scale Mach-Zehnder interferometers (MZI) coupled to dielectric resonators (DR) may be used to tune the resonance frequency of the latter. A report is presented on a theoretical study of the intrinsic tuning properties of a MZI-DR-transmission line system, of the type employed in DR oscillators, in particular, the tuning range and quality factor.

Introduction: Many methods for changing the resonance frequency of a dielectric resonator (DR) have been published, e.g. [1–3]. These approaches, in particular, either exploit mechanical, magnetic and optical schemes [1], which tend to require manual intervention and to be cumbersome to implement, or electronic, varactor-based schemes, which either include implementations that are relatively easy to realise, but tend to degrade the DR quality factor (Q) [2], or do not degrade the Q significantly, but the manufacturing of which is difficult, since they are non-planar [3]. In this Letter, a new DR tuning approach based on modulating the properties of a metallic microwave-scale Mach-Zenhder interferometer (MZI) [4], is studied theoretically. The concept, which may be implemented using micro/nanoelectromechanical systems (MEMS/NEMS) technology, is described in the following.

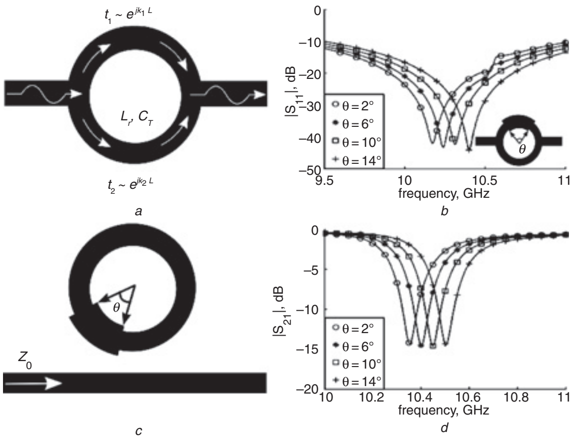

Fig. 1 *Sketch of Mach-Zehnder Interferometer (Fig. 1a); computed return loss (S_{11}) againinst frequency for various tuned-sector (i.e. asymmetric, see inset) MZI ring, with sector angle, θ, as a parameter. Structure parameters: mean ring diameter, 6.95 mm; ring trace width, 0.5 mm; substrate thickness and relative permittivity, 0.635 mm and 10.2, respectively; metallisation thickness, 0.017 mm (Fig. 1b); sketch of tuned-sector (asymmetric) MZI ring coupled to transmission line (Fig. 1c); computed microstrip transmission (S_{21}) against frequency with tuned-sector angle, θ, as a parameter (Fig. 1d); The tuned-sector width is 1 mm*

MZI-tuning mechanism description: As is well known, the propagation constant κ of the MZI ring, shown in Fig. 1*a*, is dependent on the inductance L_r and capacitance C_r per unit length

$$\kappa = \omega\sqrt{L_r C_r}$$

where ω is the wave frequency. Because of the symmetric structure, the propagation constants of the two branches are equal. This means that the input wave, after being split at the input junction, is recreated at the output junction, where recombination occurs. If a capacitive loading is added on one arm of the ring, such as results by changing its width over a certain length, as indicated in the inset of Fig. 1 *b*, then the propagation constant of that ring arm (e.g. k_1) is changed. Because of the unequal propagation constants of the two ring paths ($k_1 \neq k_2$), the resulting wave amplitude at the output junction exhibits a degree of interference, which may be anywhere between destructive and constructive. In particular, the interference caused by increasing the length of the wider arm sector manifests itself as a change in the ring's resonance frequency, as depicted in Fig. 1*b* (this, and all results in this Letter were calculated with CST [5]).

Coupling between MZI ring and microstrip line: When the MZI ring structure is coupled to a microstrip line, Fig. 1*c*, and the width of one of its arms is varied, as described above, it is observed that the transmission through the microstrip is tunable, Fig. 1*d*. This coupling, between the MZI ring and the microstrip line, is known to occur in two electric field distribution modes [6], namely, even and odd. The even mode, in particular, is identical to that via which a DR couples to a microstrip line [7]. Therefore, one would expect that coupling a ring to a DR would enable the tuning of the DR. In this context, it is necessary to determine the most appropriate size for the ring. Accordingly, a study of the radiation efficiency (RE) of the ring as a function of its diameter was conducted. The ring diameter was increased from a value such that its first mode resulted in a resonance frequency equal to $f_0 = 10$ GHz, the intended DR resonance frequency, up to a value such that its *n*th mode resulted in f_0. In other words, the ring size was scaled up progressively so that the resonance frequencies of each of its modes coincided with f_0. It was found that the ring's RE decreases with increasing mode. It is 22.3% for the first mode, and then decreases sharply to 7.31% for the second mode, and 3.47% for the third mode; it saturates at a low value for higher modes. It is important to choose a ring size that exhibits a reduced RE because, otherwise, too much of the energy coupled from the DR would be radiated and this would result in a low overall Q. Next, the tuning properties of a metallised MZI ring-DR-microstrip system are investigated.

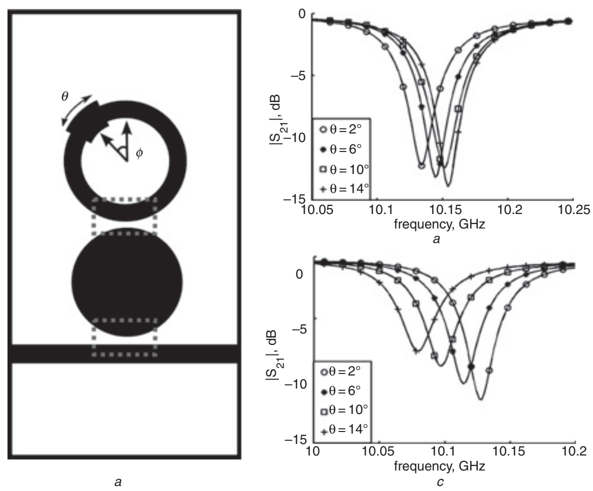

Fig. 2 *Sketch of sector-tunable MZI ring-DR-microstrip structure (Fig. 2a). DR resonance frequency 10.2 GHz; ring diameter 7.45 mm; computed microstrip transmission (S_{21}) against frequency with tuned-sector angle, θ, as a parameter (Fig. 2b). Tuned-sector width is 1 mm and its centre is at $\phi = 90°$; computed microstrip transmission (S_{21}) against frequency with tuned-sector angle, θ, as a parameter (Fig. 2c). Tuned-sector width is 1 mm and its centre is at $\phi = 30°$*

Investigation of MZI ring-DR-microstrip frequency tuning properties: The baseline MZI ring-DR-microstrip structure is depicted in Fig. 2*a*. A DR with an intrinsic Q of 5000 and a resonance frequency close to 10 GHz was chosen; a ring with diameter so that its second resonance frequency coincided with that of the DR, and whose trace width is similar to the width of the 50 Ω microstrip, was chosen. Based on extensive simulations to maximise the loaded Q of the structure (as measured from the microstrip transmission scattering parameter (S_{21})) as a function of respective DR-microstrip and DR-ring separation distances, a distance of 0.1 mm was chosen for both. The study, then, proceeded by determining, how was the S_{21}, in particular, the Q and tuning range, affected by varying the position and the length of the wider ring sector along one of the ring arms, as depicted in Figs. 2*a*. The centre of the tuning sector was positioned at a variety of angles (ϕ) and its sectoral length varied through a variety of angles (θ). The results of two such calculations are shown in Fig. 2*b*, where $\phi = 90°$, and Fig. 2*c*, where $\phi = 30°$. A general trend, typified by these two cases, is that there is a trade-off between tuning range and Q, i.e. for $\phi = 30°$, the maximum Q is 663 and the tuning range is 58 MHz, but for $\phi = 90°$, the maximum Q is 923 and the tuning range is 20 MHz. Since the examined structure in Fig. 2*a* seemed to limit the tuning and, especially, the Q, below what had been envisioned, an improved structure that increased these values was sought. Taking into consideration that, in general, higher Q and tuning range may be achieved with tighter coupling [2], a novel deformed ring and microstrip structure was conceived. This is discussed next.

Investigation of deformed MZI ring-DR-microstrip frequency tuning properties: The investigated structure, and its geometrical parameters, is shown in Fig. 3*a*. As above, the investigation proceeded by computing the Q and tuning range of S_{21}. The results are shown in Fig. 3*b* for the $\phi = 30^\circ$ case.(The $\phi = 90^\circ$ has no counterpart in the deformed ring structure.) As can be seen in Fig. 3*b*, the deformed ring structure, with its enlarged coupling area, results in a maximum Q of 956 and a tuning range of 50 MHz. This Q represents a 44% increase over that exhibited by the corresponding circular-ring structure, and a 16% decrease in tuning bandwidth, for the same change in tuning-sector dimensions, suggesting a more favourable trade-off between Q and bandwidth for the deformed-sector ring. In terms of the reduction in Q at the end of the tuning range ($\theta = 14^\circ$), relative to the initial Q ($\theta = 2^\circ$), the deformed-ring structure incurs a 62% improvement. This is favourable when compared to varactor-based DR tuning approaches, where relative Q reductions of up to 73% [2] have been reported, or other mechanical tuning approaches where relative changes of up to 74% have been obtained [8]. We focus here on relative changes in Q, rather than on absolute Q, because our goal in this Letter is to expose the properties of the intrinsic structure, i.e. independently from the manner in which the tuning sector is implemented, which may vary [1].

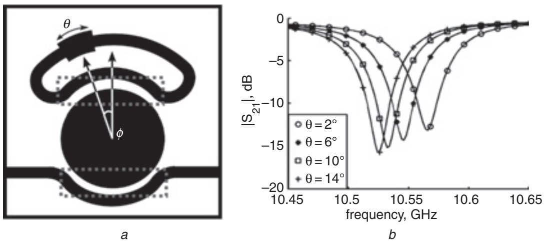

Fig. 3 *Sketch of sector-tunable MZI deformed-ring-DR-microstrip structure (Fig. 3a). DR resonance frequency 10.2 GHz; ring diameter 7.45 mm; computed microstrip transmission (S_{21}) against frequency with tuned-sector angle, θ, as a parameter (Fig. 3b). Tuned-sector width is 1 mm and its centre is at $\phi = 30^\circ$*

Conclusions: The intrinsic properties of an MZI-ring-DR-microstrip structure for utilisation in DR oscillator tuning applications have been studied. The approach is capable of effecting DR tuning while maintaining a relatively high Q and a reasonable tuning range. Based on the limitations of the circular-ring approach, a novel deformed-ring structure was conceived. The novel structure exhibits high Q and large tuning range. The MZI-based tuning concept, which involves capacitively loading the MZI ring to vary its propagation constant, may be implemented by exploiting MEMS/NEMS fabrication technology [4].

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