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100 GHz ultra-high Q-factor photonic crystal resonators

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ABSTRACT

We demonstrate an ultra-high Q-factor photonic crystal resonator operating in the millimeter-wave band, which is suitable for use as an integrated sensing platform. Experimental results show that at 100 GHz a loaded Q-factor of 5 000 and 8 700 can be achieved with a strongly and weakly coupled cavity design, respectively. The uncertainty in the experimental results has been analyzed and a new technique of propagating uncertainty in *S*-parameter measurements for the determination of Q-factor is given. The result of this uncertainty analysis gives an unloaded Q-factor of 9 040 ± 300; being fundamentally limited to ~10 000 by the intrinsic dielectric loss of the high resistivity silicon substrate. Utilizing standard bulk-micromachining of silicon, the resonators can be monolithically integrated into RFICs and MMICs for applications including liquid and gas sensing.

1. Introduction

The millimeter-wave and terahertz regions of the electromagnetic spectrum are of particular interest for sensing due to the abundance of spectroscopic features associated with molecular resonances found throughout these regions [1]. High quality (Q) factor electromagnetic resonators represent an important technology for realization of sensing systems operating in these bands [2,3]. They enable extremely sensitive detection of an analyte's complex permittivity through enhancement of the strength of interaction between the analyte and resonant mode [4].

Beyond sensing, high Q-factor resonators can be used to realize important components for future millimeter-wave and terahertz communication and radar systems, such as low phase noise oscillators and band pass filters.

Conventional room-temperature passive millimeter-wave resonators employing metal cavities or structures are generally limited in their Q-factor by losses associated with the metal features [5,6]. For this reason, dielectric resonators made from low-loss materials are preferred. Additionally, resonators which have a planar form factor are better suited toward system integration and mass production for future lab-on-a-chip devices. In Table 1, we present a summary of the Q-factors achieved by various state-of-the-art W-Band (75–110 GHz) resonators, which could be realized as part of a monolithic microwave integrated circuit (MMIC) [7]. This simple comparison is far from straightforward, as many authors fail to explain the methods used to calculate the Q-factor being quoted; either loaded (Q_L) or unloaded (Q_0).

In this paper we present an ultra-high Q-factor photonic crystal (PC) resonator. The PC has been engineered to have an electromagnetic band gap by periodic arrangement of two dielectric materials with contrasting permittivities. Similar approaches have been successfully applied at optical wavelengths to achieve high Q-factors [12] and their use for sensing has been demonstrated [13–15]; however, such high Q-factors have yet to be proven in the millimeter(mm)-wave band. Previous PC work at microwave and mm-wave frequencies has focused on demonstrating the size of the predicted band gap [16], waveguide structures [17], switches [18] and filters [19,20]; all with low Q-factors.

The specific type of PC developed for this paper has an engineered transverse electric (TE)-like (since the electric field has only in-plane components) electromagnetic band gap, created through a two dimensional periodic triangular lattice of cylinders having a

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Table 1
Previously reported W-band resonator Q-factors.

Resonator Type	Frequency (GHz)	Q-factor
Multiple ring resonator [8]	75	85
Quasi-metallic silicon PC [9]	90	25
Air-filled metal cavity [10]	94	850
Whispering gallery [11]	100	3 020

different dielectric constant to the substrate [21]. The radius of the cylinders, bulk material permittivity, thickness of the bulk material and periodicity can all be optimized in order to shift the location of the band gap. Within the lattice structure, engineered defects can give rise to allowed modes within the band gap, which can be exploited to produce resonant cavities and waveguides.

The high Q-factor resonators presented in this paper have been evaluated through simulation and measured experimental results. A rigorous analysis of the uncertainty in the Q-factor is given. Here, an analysis technique is presented that shows how uncertainty propagates from *S*-parameter measurements to Q-factor. The results clearly show that the PC design has a better performance than alternative state-of-the-art W-band resonator technologies that offer a similar compatibility for the monolithic integration of future sensing systems.

2. Design

The PC in this work is formed from a triangular lattice of air holes in a planar substrate. It is fabricated from a 525 μm thick high resistivity silicon (HRS) substrate (having the real part of the complex effective relative permittivity $\varepsilon'_{reff}(100\ \text{GHz}) = 11.64$ [22] and a dc bulk resistivity greater than 10 kΩ cm). The holes have a radius of 235 μm and a lattice constant of 780 μm. The band structure for this geometry was calculated using a plane-wave eigenmode solver [23] and the results for the lowest order modes are shown in Fig. 1. It can be seen that this structure produces an incomplete (TE-like) band gap between 97 and 127 GHz, with a center frequency at 112 GHz and a fractional bandwidth of 26%.

A resonant cavity was created in the photonic crystal by introducing a defect in the lattice; in this case formed by omitting three adjacent holes (called an L3 cavity). The mode inside the cavity is confined in-plane by Bragg reflections within the PC and out-of-plane by total internal reflections (TIRs) at the silicon-air interfaces.

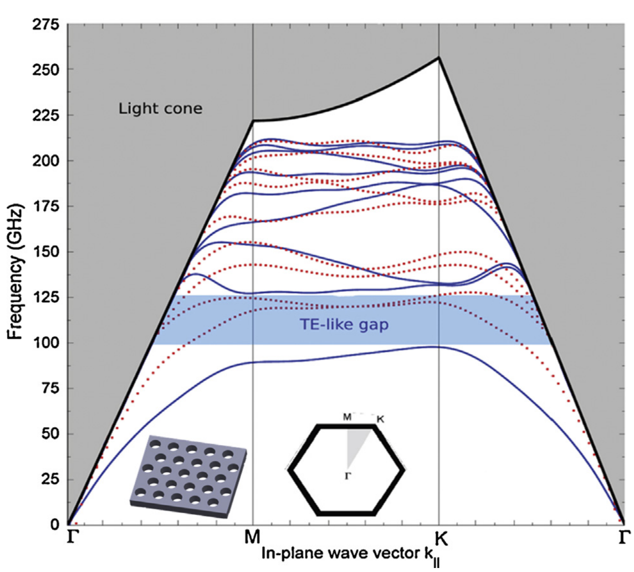

Fig. 1. Band diagram for the photonic crystal design showing the TE-like modes (blue) and TM-like modes (red dashed). The bottom left inset shows the crystal lattice structure and the central bottom inset shows the lattice Brillouin zone with the irreducible region shaded gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

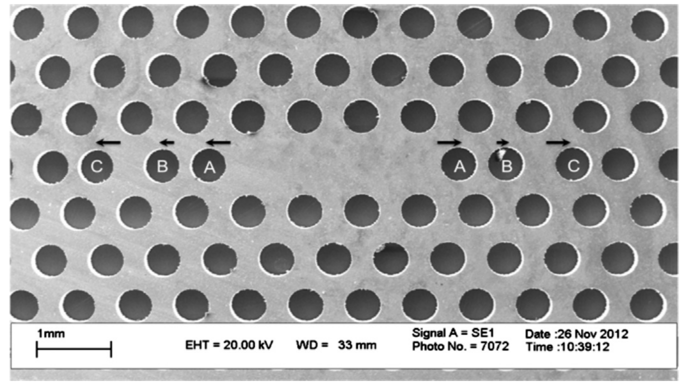

Fig. 2. Fabricated L3 cavity defect. Holes A–C are shifted away from the cavity by 156 μm, 19 μm and 156 μm, respectively.

It has previously been shown that the positioning of the holes surrounding the cavity is critical to achieving a high-Q resonance, by reducing out-of-plane radiation losses [12]. The adjustment of hole positions at the cavity edge make it possible to more gently confine the fields, allowing them to penetrate further into the crystal. A plane-wave expansion of the fields inside the cavity shows that this delocalization corresponds to a narrowing in the spatial spectral domain. This narrowing reduces components of the in-plane wave-vector $k_{\parallel}$ that do not satisfy the condition for TIR (i.e. $0 < k_{\parallel} \le 2\pi/\lambda_0$, where λ_0 is the free-space wavelength) and thereby contribute to radiation loss. Further details of this effect can be found in [12,24]. To minimize radiation losses in our design, the three holes on each side adjacent to the cavity (starting from the closest hole) were shifted 156 μm, 19 μm and 156 μm away from the cavity, in relation to their normal lattice positions, as is shown in Fig. 2.

To couple energy into the cavity, a W1 defect feed waveguide was created by omitting a partial row of adjacent holes in the PC lattice. Three different W1 defect waveguide configurations were considered – one with the W1 defect feed waveguides inline below the cavity. The other two have the feed waveguides offset above and below the cavity, to reduce mutual coupling. With the offset configuration, two different lengths of W1 waveguide were considered, to provide weak and strong coupling to the cavity, as shown in Fig. 3. A weak coupling provides a better estimation of the unloaded Q-factor as $Q_0 = Q_L/(1-\kappa)$ [25], where Q_L is the loaded Q-factor and $\kappa = |S_{21}|$ where κ is the coupling factor. This means that for the weakly coupled PC with a resonant peak at −40 dB, Q_L will be within 1% of Q_0.

To couple a TE-like mode into the W1 defect feed waveguide, a triangular taper is created at the edge of the substrate, so that it can align to and fit inside a standard WR10 waveguide aperture [26], as illustrated in Fig. 4. The triangular taper was 2.1 mm long

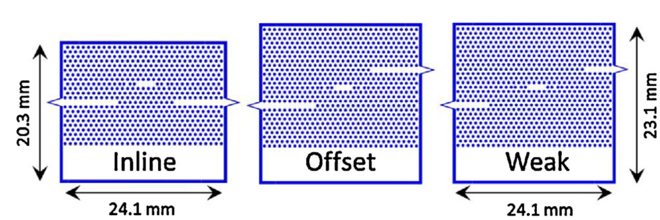

Fig. 3. Three PC resonator designs with the blue dots denoting air holes in the white HRS substrate. The left design has the excitation W1 defect feed waveguides inline and the other two have the offset configuration. The resonator on the right is weakly coupled, while the other two are strongly coupled.