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Hilbert-Pair Shaped Resonator for Ku-Band Applications

Mustafa Mahdi Ali [1,2], Enrique Márquez Segura [1], T. A. Oleiwi [3]
[1]Telecommunication Research Institute (TELMA), E.T.S. Ingeniería de Telecomunicación, Universidad de Málaga
Boulevard Louis Pasteur 35, 29010, Málaga, Spain
[2]Electrical Engineering Department, College of Engineering, Mustansiriyah University
Palestine Street, Baghdad, Iraq
mustafa_mahdi@uma.es; mustafa_mahdi@uomustansiriyah.edu.iq;
ems@ic.uma.es
[3]Islamic University Centre for Scientific Research, The Islamic University, Najaf, Iraq
iatrcbaghdad@gmail.com

Abstract – The Ku-Band is a crucial part of the electromagnetic spectrum widely employed in satellite communications, radar systems, and other high-frequency applications. To enhance the performance of Ku-Band devices, such as novel resonator structures have been investigated. The Hilbert Resonator has shown promise due to its unique characteristics. This paper introduces the Hilbert resonator and conducts a comprehensive literature review to highlight its potential applications, design methodologies, and performance advantages in the context of Ku-Band technologies for their unique propagation properties and high data rate capacity. The proposed resonator is developed based on the second iteration of Hilbert-shaped fractal geometry. The proposed resonator is developed from a number of unit cells to suit the applications of Ku-band systems. Therefore, five-unit cells are introduced; each unit cell is constructed from a pair of Hilbert curve geometry. This number is considered after a comprehensive parametric study to recognize the optimal required number of unit cells. The proposed design is printed on Roger substrate to occupy an area of $30\times35\text{mm}^2$ when coupled to a 50Ω microstrip line. It is good to mention that the proposed resonator shows S_{12} -17dB at 14.25GHz. Our work is developed using a numerical parametric study based on CST MWS to determine the optimal design. We validated the obtained results from the optimal design using HFSS numerical simulations. Finally, a great agreement is achieved between the simulated results based on the involved software packages.

Keywords**:** Hilbert, fractal, resonator, Ku-band.

1. Introduction

The ever increasing demand for high-speed data transmission in communication applications and advanced radar systems has driven the need for efficient and compact resonator structures in the Ku-Band frequency range (12-18 GHz) [1]. In [2], Hilbert resonator was discussed to evaluate the electromagnetic structure that has attracted considerable attention due to its unique properties and potential applications. Therefore, this paper briefly overviews Ku-Band technology, its significance, and its applications in modern communication and radar systems.

The Hilbert Resonator is a type of electromagnetic resonator that finds applications in microwave engineering in the Ku-band frequency ranges [3]. The resonator's characteristics make it suitable for compact high-Q (quality factor) filter designs. For instance, a design was introduced in [4] to explore the concept of Hilbert resonators and discuss their properties. It presents design methodologies and analyzes the resonator's characteristics using numerical simulations. The work in [5] focuses on designing and implementing compact filters based on Hilbert resonators for Ku-band applications. It discusses the advantages of using Hilbert resonators and presents the measurement results of fabricated filters. In [6], a design was presented to explain the approach for miniaturizing microwave filters utilizing Hilbert resonators. It discusses the coupling mechanism between the resonators and provides

experimental results for filters operating in the Ku-band. Another work was proposed in [7] to explore a design based on a compact Hilbert resonator-based filter design for Ku-band applications. The authors propose a miniaturization technique and evaluate the filter's performance using electromagnetic simulations and experimental measurements.

Numerous designs based on different fractal geometries have been presented in the last two decades [8]. In [9], an exploration was developed the use of fractal resonators in the design of electromagnetic band gap (EBG) structures for low-profile antenna applications in the Ku-Band. An investigation was developed in [10] using fractal resonators in metamaterial absorber-based on miniaturized antennas, demonstrating their effectiveness in achieving broadband absorption and reduced radar cross-section (RCS) in the Ku-Band. A comparative analysis was explored in [11] to investigate the performance advantages of Sierpinski fractal resonators over conventional designs, highlighting their multiband behavior and improved performance in the Ku-Band. A study was introduced in [12] to present a tunable and frequency-selective surface based on fractal Hilbert geometries, demonstrating their capability to achieve high-performance Ku-Band filtering. A survey paper was proposed in [13] to provide an overview of microfabrication techniques, including microelectromechanical systems, which can be employed to fabricate high-precision geometries in Ku-Band devices. In [14], a paper was devoted to present micromachined Ku-Band filters and switches, demonstrating the feasibility of using microfabrication techniques for the fabrication of fractal resonators. Recent advancements in fractal-inspired multiband and broadband antennas for future wireless communication systems were discussed in [15], providing insights into the potential future applications of fractal resonators in the Ku-Band.

2. Resonator Design Details

The proposed resonator is designed using 2nd iteration of a Hilbert fractal geometry with a trace width of 0.5mm. in such design the maximum reflection is achieved at 14.25GHz with minimum transmission around -30dB. This is achieved when the same fractal geometry is duplicated opposite to each other with respect to the center of the Roger 5880 substrate as in Fig. 1. It is good to mention that the authors did not increase the fractal iteration beyond the 2nd iteration to avoid inconvenience crosstalk or coupling between traces. The reason for duplicating the Hilbert geometry is to create a balance in the current motion that circulates electrical charges in opposite directions to each other to cancel the internal field accumulation, which realizes high stability in the resonator performance with increasing the number of unit cells. Therefore, the achieved multipath reflections (S_{11}, S_{22}) phase difference between the unit cell edges and the microstrip line reaches zero at the frequency band of interest. The proposed unit cell is inductively coupled to a 50Ω microstrip line. The coupling distance between the proposed unit cell and the transmission line is considered 0.84mm, as shown in Fig. 1. This distance is considered to avoid the direct touch, which realizes field fringing losses. Such coupling ensures the RF energy flow from the transmission line toward the unit cell with minimum storing losses.

In this work, the proposed design is fabricated on the Roger substrate with 0.8mm thickness and a size of 30mm×35mm that realizes an excellent size reduction at the frequency band of interest. The proposed resonator is shown in Fig. 1 with all geometrical details.

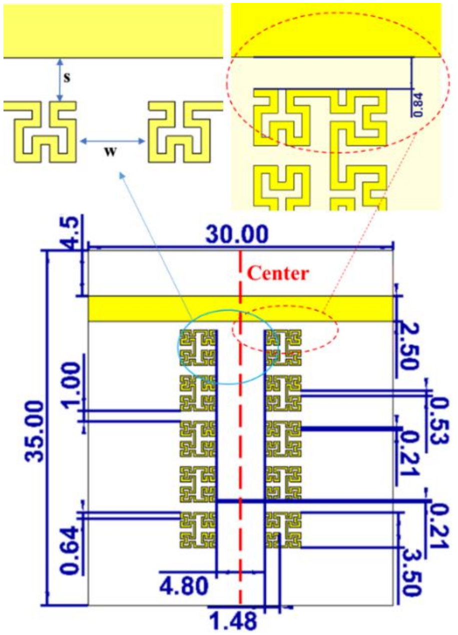

Fig. 1: The proposed resonator geometry.

3. Design Methodology

In this section, the design methodology of the proposed resonator is discussed. Therefore, we conducted a numerical simulation based on CST microwave studio to evaluate the effect of the fractal iteration order, the coupling distance between the microstrip line and the unit cell, and the unit cell number.

3.1. Iteration Order

In this section, the effects of changing the iteration number of the proposed fractal are investigated. As shown in Fig. 2, the evaluated performance of the proposed unit cell based on Hilbert fractal geometry in terms of S_{11} and S_{12} is shown. It is found that the proposed unit cell shows a frequency resonance of about 15.5GHz at the zeroth order, 14GHz at the first order, and about 14.25GHz when the second iteration is introduced. Such observations realized that increasing the number of fractal iterations could significantly affect a frequency band resonance and the magnitude of well-matching. This could be attributed to the effects of equivalent variation on the capacitive, inductive load with respect to the varying unit cell iteration.

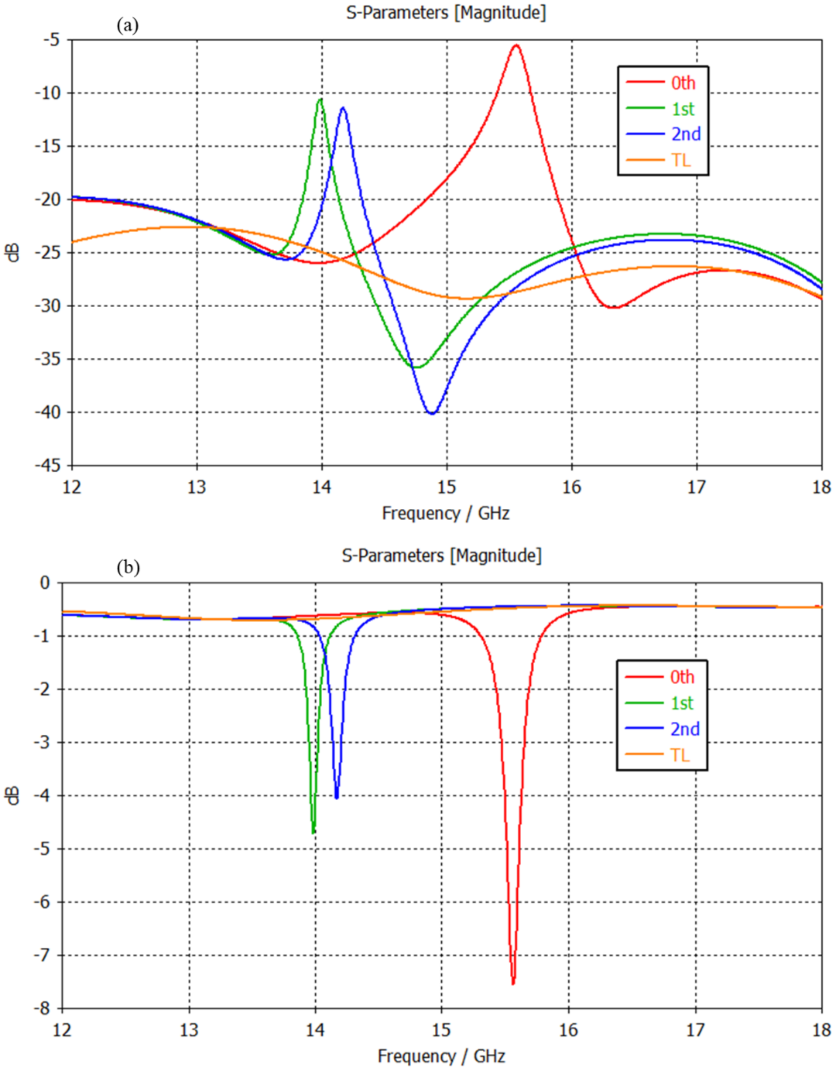

Fig. 2: The effects of changing the fractal iteration on the S-parameters: (a) S_{11} (b) S_{12}.

3.2. Coupling Effects

In this section, the proposed unit cell pair is separated horizontally, with a specific guard distance (w) of 0.8mm; this distance is considered to avoid direct coupling or shorting between the unit cells. Therefore, studying the effect of increasing this distance on the proposed resonator performance requires varying this distance parametrically. For this, the authors increased the separation distance (wt) from 1.8mm to 9.8mm with a step of 2mm. It is observed that such change effects severely on the unit cell resonance as well as the bandwidth. This is due to capacitive coupling between the unit cell pair. In other words, an electric charge accumulation increases rapidly with decreasing the separation distance that is subjected to storing losses and fringing phenomena. Therefore, it is found that tuning the resonance frequency at the desired band can optimize the separation distance to reach the desired frequency band. In Fig. 3, the obtained S-parameters are depicted for the above discussion.

Now, the same previous study is applied to the vertical distance (s) to realize the effect of that distance on S-parameters. It is found from the obtained results shown in Fig. 4, a severe degradation in the resonance matching impedance due to the variation in surface wave that increase phase retardations. That could be attributed to the effects of a reduction in the electromagnetic coupling.

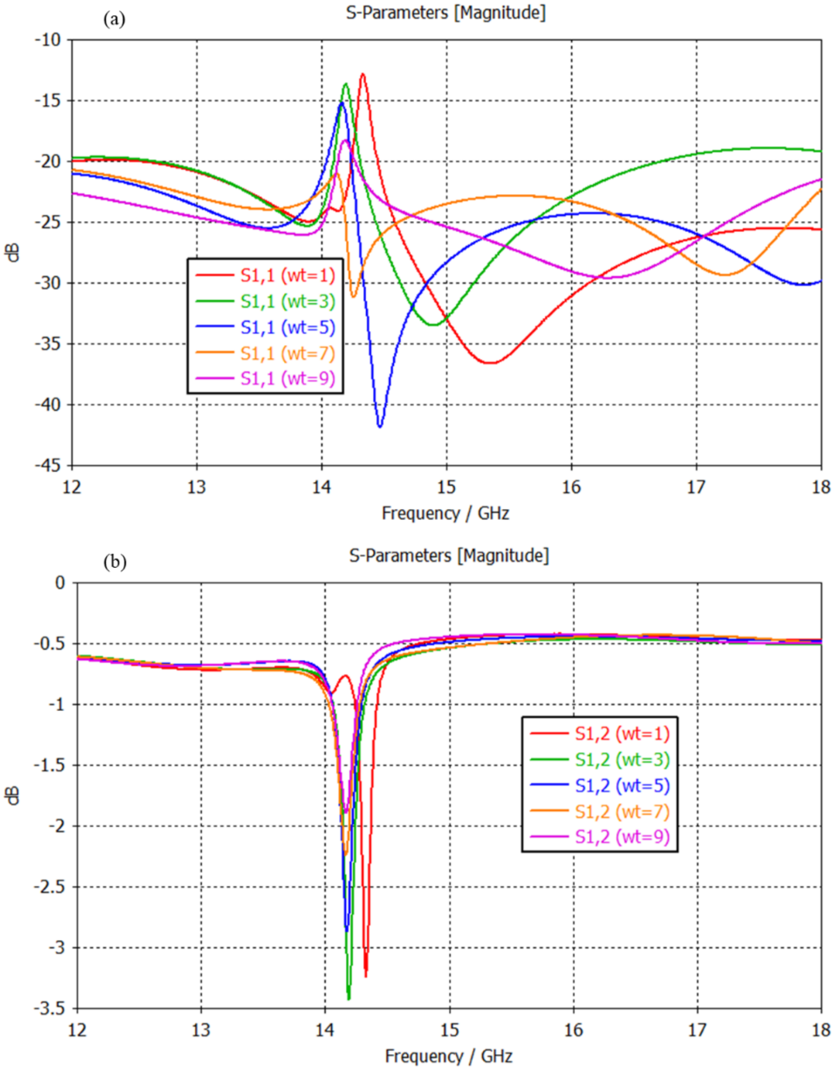

Fig. 3: The effects of changing the horizontal separation distance on the S-parameters: (a) S_{11} (b) S_{12}.

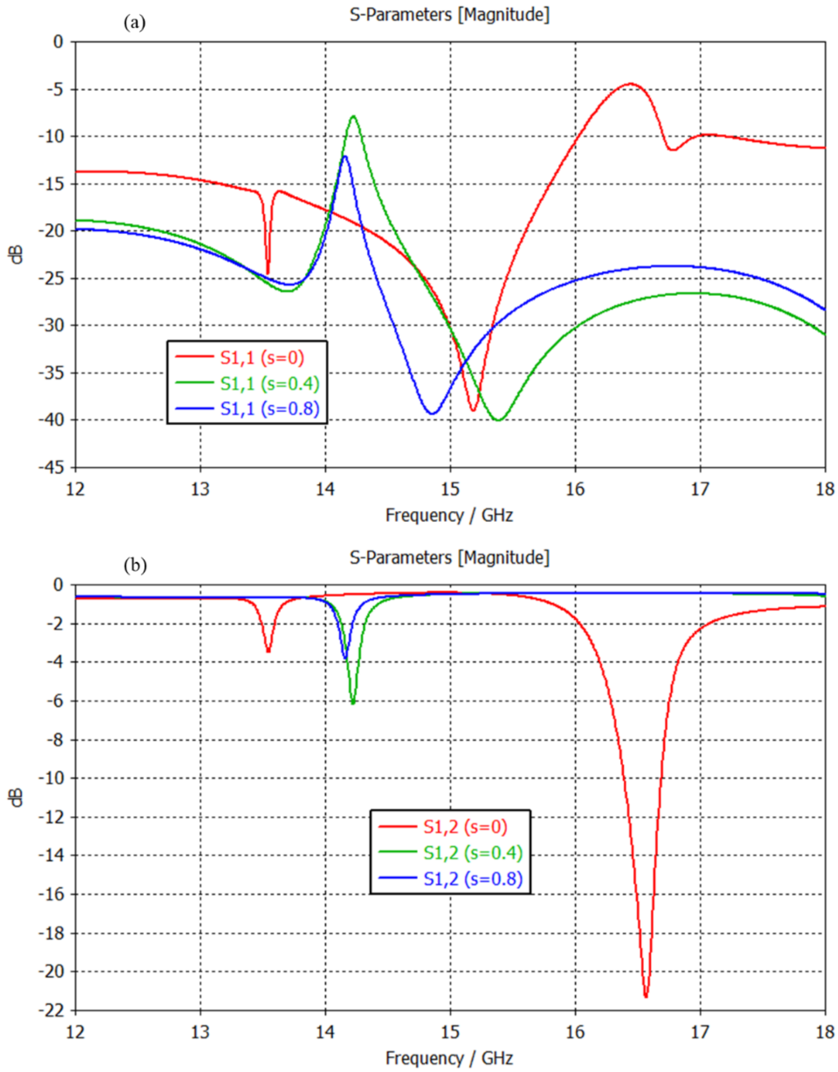

Fig. 4: The effects of changing the vertical distance on the S-parameters: (a) S_{11} (b) S_{12}.

3.3. Unit Cell Number

The effect of varying the unit cell number is studied in this section by changing their number up to 5-unit cell. The evaluated S-parameters are shown in Fig. 5. It is obvious that the main effects of varying the unit cell number are attributed to a change in matching level more than any change in the bandwidth. This is due to the fact that increasing the unit cell number is just a matter of increasing inductive, capacitive branches without any effect on the effective electrical surface current motion. We can conclude from such observations that an ineffective variation could occur after making the unit cell number equal to five. This is because the internal impedance of the equivalent unit cells increases rapidly with increasing their number that are connected electrostatically in a series manner.

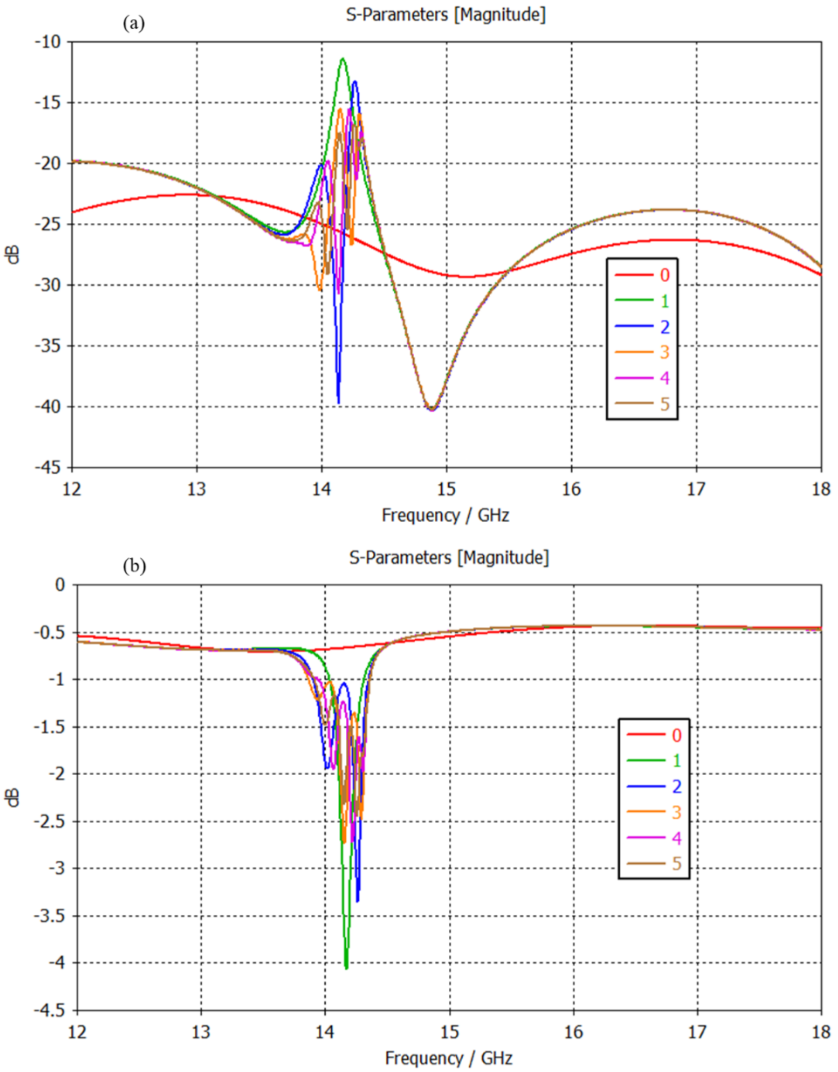

Fig. 5: The effects of varying the unit cell number on the S-parameters: (a) S_{11} (b) S_{12}.

4. Results Validation and Discussion

To validate the obtained results from the previous section, another numerical simulation based on finite element method (FEM) is invoked. The obtained results from both methods, FEM and Finite Integral Technique (FIT), in terms of S-parameters, are presented in Fig. 6. Numerically, it is found a good agreement achieved between both methods; that ensures our adopted methodology is quite a valid technique. Finally, a comparison in Table I is introduced to compare the performance of the proposed resonator with respect to the relative published in the literature. From the comparison it is obvious that our proposed unit cell achieves a bandwidth that is quite used in the modern applications at the Ku-band communication systems.

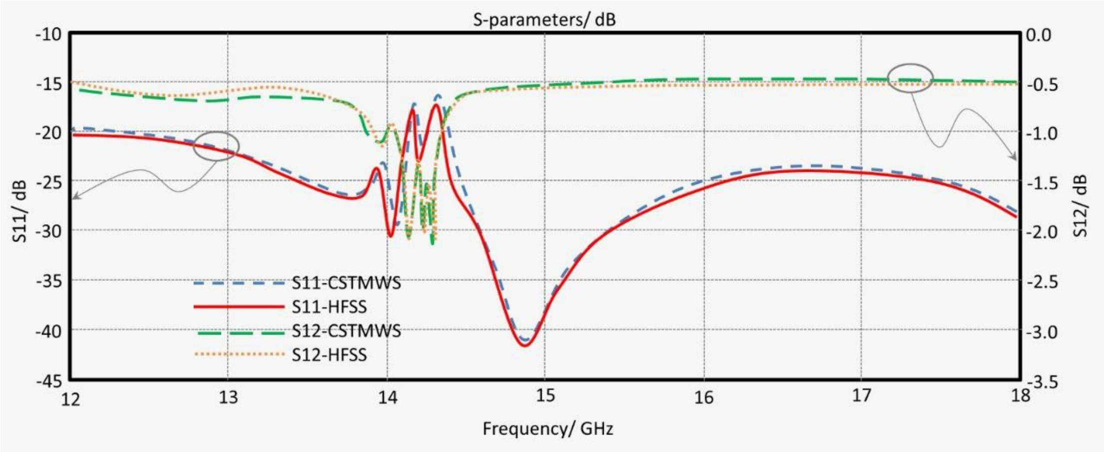

Fig. 6: The S-parameter validations in terms of S_{11} and S_{12}.

Table 1: Comparison between the proposed resonator and others published in the literature.

Ref.	Structure	Unit cell size (mm^2)	Band	S_{12}
[16]	Tuning fork	8 × 8	C-Ku	-1.0
[17]	L-shape	8 × 8	X	-2.4
[18]	S-shape	20 × 20	S-, X-, Ku	-4.5
[19]	L-shape	9 × 9	X-, Ku	-1.2
[20]	Square shape	10 × 10	C-, X-, Ku	-1.3
[21]	O-shape	12 × 12	X	-0.5
[22]	Modified square	8 × 8	X	-0.75
The proposed work	Hilbert	30×35	Ku	-17

5. Conclusion

In this paper, the performance of the microwave resonator based on Hilbert geometry of the 2nd iteration metamaterial unit cell is constructed. The proposed design is basically developed from a transmission line coupled to five pairs of the metamaterial unit cell. The proposed structure is designed to operate over the frequencies of the Ku-band. When the proposed design is mounted on Roger substrate, it is found to provide a frequency resonance at 14.25GHz to occupy an area of $30\times35mm^2$. The obtained results are validated using two commercial software packages to agree well.

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