Multifrequency Seashell Slot Antenna With Cold-Electron Bolometers for Cosmology Space Missions

Leonid S. Kuzmin, Alexander V. Chiginev, Ekaterina A. Matrozova, and Alexander S. Sobolev

***Abstract*—A novel type of the "seashell" multichroic polarized antenna is proposed for cosmology space missions. The polarized slot antennas are arranged in the compact form of a seashell with individual slots for each frequency and each polarization. Such an arrangement gives a unique opportunity for independent adjusting individual parameters of slots with microstrip lines (MSLs) and bolometers. For each frequency band, the seashell antenna contains two pairs of orthogonal slots for each polarization connected by MSLs with a bolometer in the middle for in-phase operation. To fit slots in the $\lambda/2$ area for the best beam shape, lumped capacitances in the form of the H-slot were introduced. Ellipticity of a beam was improved to the level of better than 1%. The seashell antenna gives a unique opportunity to select the needed bandwidth using two options. The first option is the frequency selection by resonance properties of slots with MSLs and resistive cold-electron bolometer (CEB). The second option is the frequency selection by resonant CEB with an internal nanofilter organized by a kinetic inductance of the NbN superconducting nanostrip and a capacitance of the nanoscale superconductor–insulator–normal tunnel junction.**

***Index Terms*—Capacitance of SIN junction, lumped capacitance resonant cold-electron bolometer, NbN kinetic inductance, seashell slot antenna.**

I. Introduction

RECENTLY, the detection of gravitational waves was announced as a result of the American experiment Background Imaging of Cosmic Extragalactic Polarization (BICEP2) [1]. Gravitational waves formed in the early evolution of the universe, had to leave their marks in the vortex B-mode polarization of the CMB in accordance with the existing theoretical concepts. B-mode was observed by a phased array of slot antennas. However, these results are in contradiction with dust measurements of Planck [2] and should be checked at different frequencies.

The measurement of the CMB polarization is included in the ambitious COSMIC VISION 2015–2025 program of the European Space Agency (ESA). The COrE+ and SPICA space missions are under consideration by ESA. The important goal for the ESA is to reduce size of the focal plane by placement of the multifrequency array of detectors for simultaneous data acquisition [3]. Such an approach would solve the problem of the aberration and uniformity of the beam pattern across the total focal plane.

Success in solving the problem can be achieved through the use of the recently invented resonant cold-electron bolometer (RCEB) [4] in combination with multichroic antennas. An internal nanofilter of the RCEB is organized by a kinetic inductance of the NbN superconducting nanostrip and a capacitance of the nanoscale SIN (Superconductor-Insulator-Normal) tunnel junction. The kinetic inductance is about 300 times smaller than the geometrical inductance of the same value. This internal resonance acts as a bandpass filter with a bandwidth of 3–50% needed for radioastronomy applications.

Another option is frequency selection by resonance properties of slot with MSLs and resistive Cold-Electron Bolometer (CEB) [5]–[7]. One of these options of frequency selection by RCEB or slot antenna can be chosen depending on tasks and requirements on bandwidth selection for multifrequency systems.

As a promising candidate of the multichroic systems, a novel "seashell" slot antenna has been proposed for this goal. The antenna is called seashell due to the similarity of round loops of slots for different frequencies with a seashell. The seashell slot antenna is the multichroic system which has several key advantages compared to other concepts: sinuous [8], and cross-slot [4], [9]. The main advantage of the seashell antenna in comparison with sinuous and cross-slot antennas is that it provides the opportunity to tune independently separate slots for each frequency. It is also quite compact and can be easily extended to a larger number of frequency channels by adding proper slots. Moreover, this extension will not increase the size of the system because all new slots will be positioned inside the larger slots. In the present paper we report on computer simulations of various modifications of the seashell antenna designed for two frequencies—75 and 105 GHz. However, in the first section we describe the example of 4-frequency antenna to demonstrate the possibilities of such a concept.

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(a)

(b)

(c)

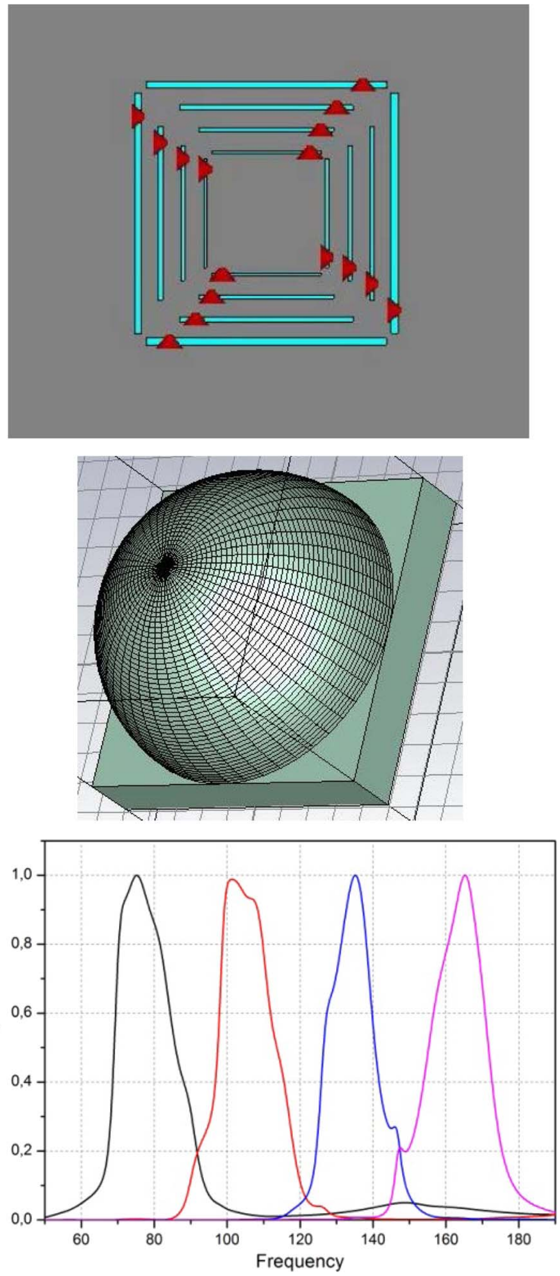

Fig. 1. (a) Central part of the seashell antenna with RCEBs. (b) General view of the system with a lens. (c) Absorption versus frequency for 75, 105, 135, and 165 GHz.

II. Seashell Antenna With $\lambda/2$-Slots

A. Seashell Multichroic $\lambda/2$-Slot Antenna With CEBs

A view of the central part of the seashell antenna for 4 frequencies is shown in Fig. 1(a). It consists of 16 slot antennas: two antennas for each frequency of 75, 105, 135, and 165 GHz, and each polarization. Discrete ports are placed inside the slots and shifted from the center of slots to reduce the matching impedance with the RCEB. Parameters of slots and ports position were determined for each frequency separately. To focus the beam, 9 mm silicon lens with antireflection coating of quartz with thickness of 430 microns is used [Fig. 1(b)]. In simulations we use simultaneous excitation of the ports located at opposite slots. We model RCEBs as LCR circuits with frequencies tuned to desirable channels.

The absorption is presented in Fig. 1(c). One sees that providing the proper parameters for each LCR circuit, the seashell antenna demonstrates good frequency selection. The polarization resolution is quite acceptable: -16 dB, -28 dB, -20 dB, and -13 dB for 75, 105, 135, and 165 GHz, respectively. However, beam ellipticity appears not to be perfect:10%, 12%, 22%, and 46% at 75, 105, 135, and 165 GHz, respectively. To overcome this difficulty, one needs to squeeze the slots.

The variant of the seashell antenna described above is most common one, just showing the possibility of such an antenna to work with several frequency bands. Further we will consider more specific examples and restrict ourselves to the case of two-frequency antenna. However, the expansion to more frequencies can be done by simple insertion of extra slots into the central part of the antenna.

B. Seashell $\lambda/2$-Slot Antenna With MSLs and CEBs

For tuning parameters of the seashell antenna with $\lambda/2$ slots, we discovered that for further improvement of the beam ellipticity we need to move the opposite slots closer to distance around $\lambda/2$. However, the geometrical size of the slots plus extra space did not allow us to do it. To overcome this geometrical limitation the concept of the seashell antenna with H-slot geometry and lumped capacitances was proposed. This concept allows realizing a smaller size of slots and more freedom in position of slots for tuning optical parameters. The seashell antenna with lumped capacitances is shown in Fig. 2(a).

For phase connection of slots it is necessary to collect the received signals from the slots by MSLs and bring them to a bolometer in the center. The seashell slot antenna with H-slots and MSL for two polarizations is shown in Fig. 2(a).

Let us consider the approach to obtain the serial resonance at certain frequency. In Fig. 3(a) one can see that the serial resonance at 75 GHz is located between two strong parallel resonances. Fig. 3(b)–(d) show the structure of these resonances. The first resonance at 62.8 GHz is characterized by nearly uniform distribution of the phase of the electric field along the slot. For the second resonance at 84.4 GHz the phase of the electric field exhibits a 180° flip at a certain coordinate related with the position of the stub. The location of the serial resonance between two parallel ones actually determines its frequency, and the bandwidth of this resonance.

This antenna provides beam ellipticities of 3.5% and 2.7% at 75 GHz, horizontal and vertical polarizations, respectively, and 4.3% and 4.7% at 105 GHz, horizontal and vertical polarizations, respectively. The bandwidths are over 20% at 75 GHz slots and nearly 20% at 105 GHz slots [Fig. 2(b)]. However, cross-polarization suppression is relatively low at 75 GHz, vertical polarization [Fig. 2(c)]. Besides, there is a parasitic resonance at 75 GHz curve, vertical polarization [Fig. 2(b)]. Though, as we can see further, this type of the antenna is the most promising one for the purposes of CORE mission.

Advantages of the seashell antenna with $\lambda/2$ H-slots:

- The beam ellipticity $< 5\%$.
- Bandwidths at -3 dB meet ESA requirement—20% of operation frequency.
- ReZ at resonant frequencies is acceptable for matching with CEB.

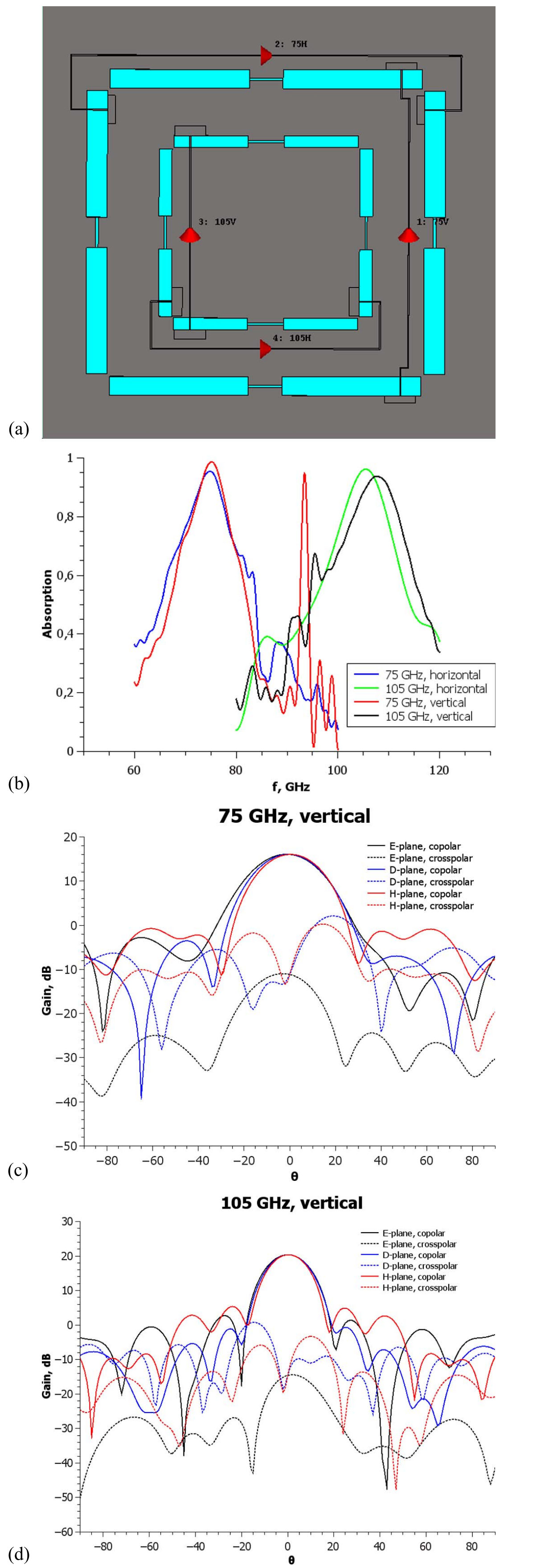

Fig. 2. (a) Seashell antenna with H-slots. (b) Absorption versus frequency for horizontal and vertical polarization. (c) and (d) Radiation diagrams for vertical polarization at 75 and 105 GHz, respectively.

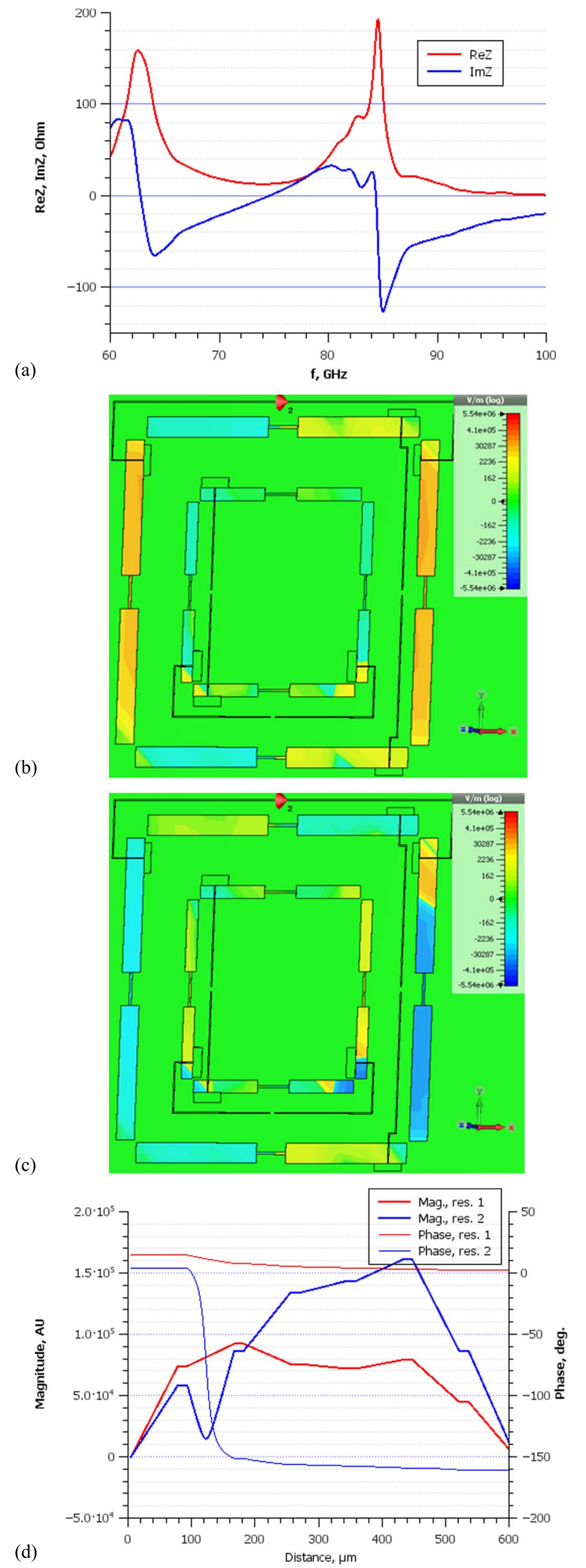

Fig. 3. Structure of resonances in 75-GHz slot of the seashell antenna. (a) ReZ, ImZ versus frequency. (b) and (c) Two-dimensional electric field distribution along the slot at first (62.8 GHz) and second (84.4 GHz) parallel resonances. (d) Magnitude and phase distribution of the electric field in the slot.

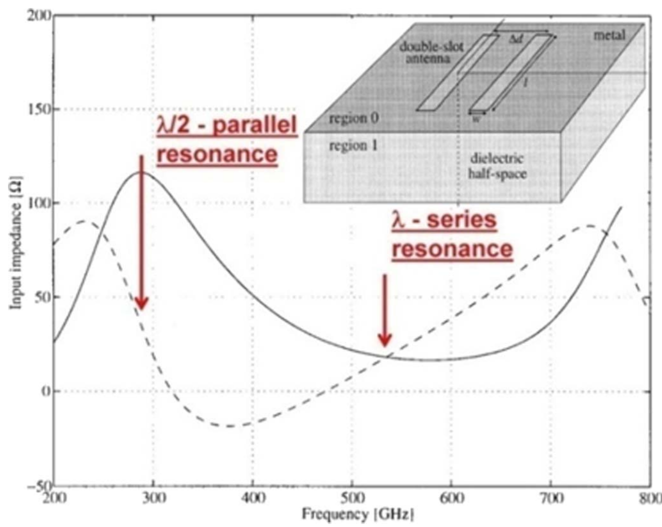

Fig. 4. Impedance of a double-slot antenna (ReZ, ImZ) with $\lambda/2$-parallel and λ-series resonances.

Disadvantages of the seashell antenna with $\lambda/2$ H-slots:

- Presence of parasitic resonance at 75 GHz slot for vertical polarization.
- The suppression of cross-polar component is a bit insufficient.

III. Seashell λ-Slot Antenna With Lumped Capacitances

A. Seashell λ-Slot Antenna With Lumped Capacitances and CEBs

The analysis of $\lambda/2$ slots has revealed several disadvantages of the antenna based on this type of slots. First, they provide insufficient suppression of cross-polar component of an incident radiation. This is probably due to nonsymmetric feeding of slots. The second drawback is the presence of parasitic resonances.

The special type of λ-slots with lumped capacitances by double H-slots with dual narrowing has been proposed to avoid disadvantages of the previous system. The main attraction of λ-slots is transition from high-ohmic parallel resonance to serial resonance with reasonable resistance [10] for matching with MSL and CEB (Fig. 4). This gives the possibility of connection of MSLs to the center of the slots, providing thus the symmetry of the system and improvement of cross-polarization suppression.

As in the previous part, we start with the case of the antenna without MSLs, assuming simultaneous excitation of opposite slots.

The design of the seashell antenna with λ slot with lumped capacitances for two polarizations is shown in Fig. 5(a). The inner corners of the slots were cut at 45 degrees for maximum close position of the slots. This distance should be of the order of $\lambda/2$ that is important for the beam shape.

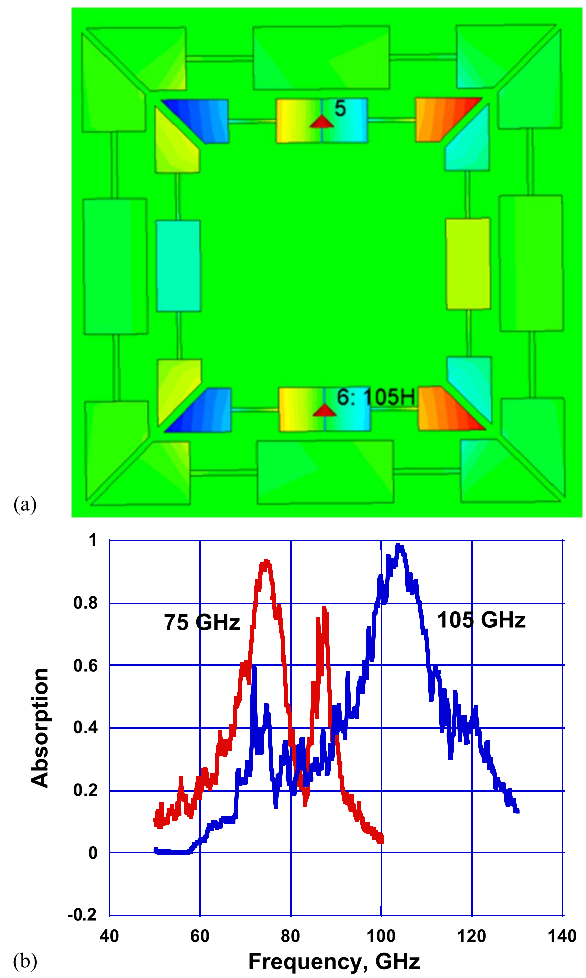

Fig. 5. (a) Seashell antenna with λ double-H slots for two polarizations with distribution of magnetic field. Excitation of 105-GHz slots. (b) Absorption versus frequency for the seashell slot antenna with lumped capacitances for 75 and 105 GHz.

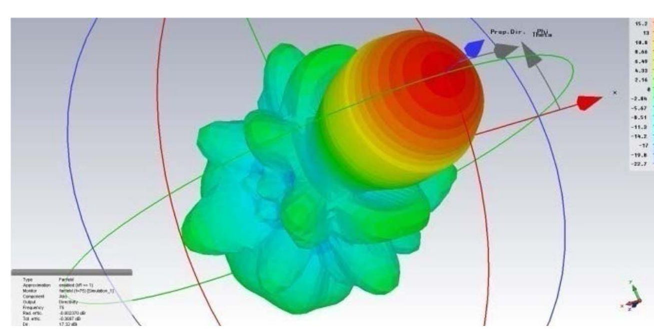

Fig. 6. Radiation pattern for the horizontal polarization at 75 GHz.

Only ports for horizontal polarization were excited in this analysis. Absorption for 75 GHz channel is shown in Fig. 5(b). The bandwidth is 11 GHz for horizontal polarization.

The beam for 75 GHz is presented in Fig. 6. The 75 GHz channel demonstrates very good beam performance: ellipticity is 0.4%, beam width is 24.2°, sidelobe level −18.3 dB. Cross polarization is −24 dB.

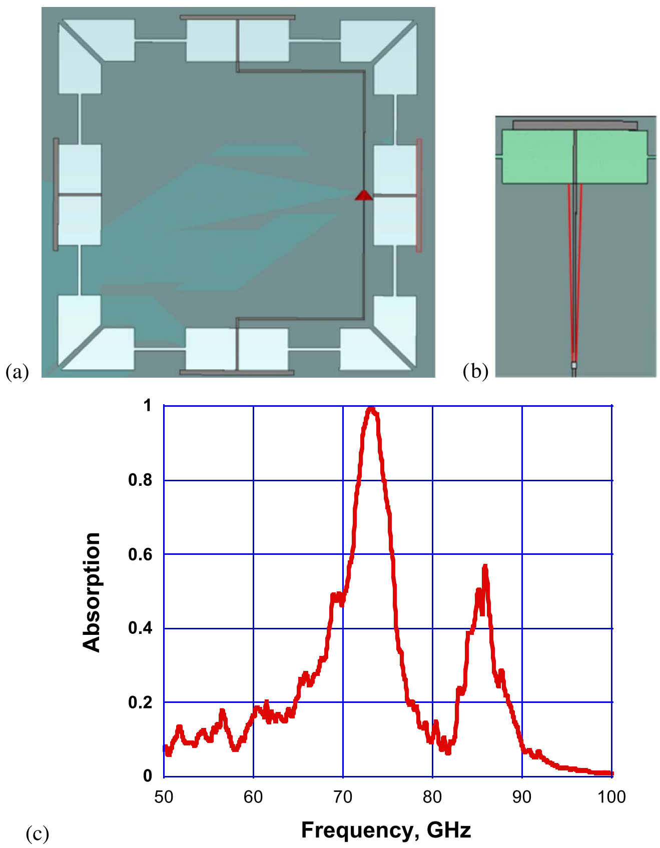

Fig. 7. (a) Full scheme of a seashell with taper and bolometer for 75 GHz. (b) Schematic of a taper in MSL. (c) Absorption versus frequency for horizontal polarization.

Advantages of the seashell antenna with λ H-slots:

- More flexibility than in a system with the ordinary λ slots.
- The cross polarization is quite low < -24 dB.
- The presence of the series resonance instead of poorly controlled parallel resonance.

Disadvantages of the seashell antenna with λ H-slots:

- The wide H-slots limit flexibility in distance between slots.
- The bandwidth is reduced to level lower than 15 GHz.

One can conclude that the seashell λ-antenna with lumped capacitances is an interesting configuration for further development.

B. Seashell λ-Slot Antenna Phased by MSLs With CEB

To phase a signal from slots MSLs should be used. The λ-slot antenna with MSLs is shown in Fig. 7(a).To match the low impedance in the center of the slot with the impedance of CEB we use taper in MSL. Schematic presentation and total scheme of a seashell with a taper are shown in Fig. 7(a) and (b).

Absorption for each polarization is shown in Fig. 7(c). The bandwidth is rather narrow about 5 GHz. Beam ellipticities are 7.5% and 3.5%, beam widths are 25.7° and 15.1°, sidelobe levels are -13.9 dB and -12.6 dB for 75 and 105 GHz, respectively. Cross polarization is -24 and -32 dB for 75 and 105 GHz, respectively. The ellipticity is almost satisfactory, especially at 105 GHz. ReZ is increased to the level of 22 Ohm at the resonance due to a taper (Fig. 8). It's a good figure for matching with CEB. However, bandwidth is at the level of 5 GHz that is not enough for applications. The reason of small bandwidth is parasitic parallel resonance that is just nearby the useful resonance. Due to unlucky coincidence, this resonance is $3\lambda/2$-resonance of the slot that is "pulled out" by MSL to just position of the useful 2λ-resonance. Some parameters of system, such as dimensions of the components of the antenna, should be modified to tune it out of useful bandwidth.

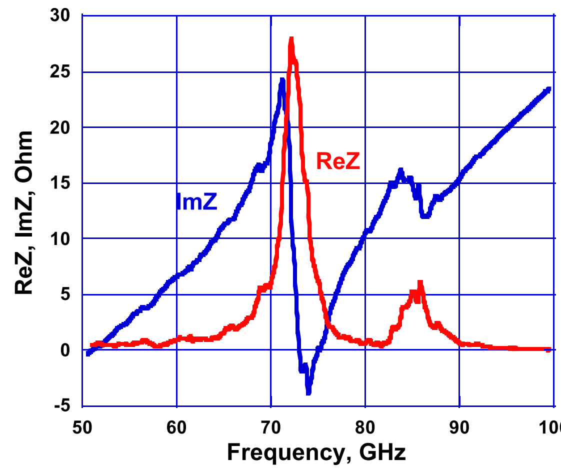

Fig. 8. Impedance versus frequency for horizontal polarization.

The summary of the seashell antenna characteristics is shown in Table I. It is seen that λ-slot antenna has acceptable beam parameters, but narrow bandwidth, which restricts its applicability for COrE mission. On the other hand, $\lambda/2$-slot antenna has acceptable both beam and frequency characteristics, and in this sense it represents more appropriate candidate for COrE. Nevertheless, λ-slots can be used in applications which require narrow bandwidth, e.g., in LSPE balloon mission.

IV. Conclusion

A new type of a seashell slot antenna is proposed in this paper. The polarized seashell antennas are arranged with individual slots for each frequency that gives unique opportunities for independent adjusting parameters of antennas and bolometers. Lumped capacitances are proposed for squeezing slots and getting perfect ellipticity due to decrease of slots and more freedom in mutual position of slots.

The seashell antenna gives an opportunity to select needed bandwidth using resonance properties of slots or resonant cold-electron bolometers with an internal nanofilter by a kinetic inductance of the NbN nanostrip. For bandwidth of 20% the optimal configuration proved to be a seashell $\lambda/2$-slot antenna with lumped capacitances and MSLs with CEBs. This configuration is using resonant properties of slot antennas. Matching with microstrip lines and bolometers can be done by tuning position of stubs relatively to the ends of slots. The seashell antenna has possibility of easy expansion to more than two frequencies by insertion of the next loops inside previous ones.

TABLE I
SUMMARY OF THE SEASHELL ANTENNA CHARACTERISTICS. INDICES H AND V POINT TO CHARACTERISTICS RELATED TO HORIZONTAL AND VERTICAL POLARIZATION, RESPECTIVELY

	1B		2A		2B	
	75 GHz	105 GHz	75 GHz	105 GHz	75 GHz	105 GHz
Ellipticity, %	3.5 (H) 2.7 (V)	4.3 (H) 4.7 (V)	0.4		7.5	3.5
Beam width, °	26.5	16.8	24.2		25.7	15.1
Crosspolarization, dB	-18.5 (H) -12.5 (V)	-20.9 -21.0	-24		-24	-32
Sidelobe level, dB	-15.1	-15.1	-18.3		-13.9	-12.6
Bandwidth at -3 dB, GHz	18.8 (H) 15.4 (V)	19.3 (H) 22.3 (V)	10.6	13	~5	~5
Parasitic resonances, GHz	93 (V)	-	87	120	85	-

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