Compact radial combiners for broadband high power applications

Alexei V. Smirnov

RadiaBeam Systems LLC, 1713 Stewart St., Santa Monica, CA 90404, US

Multi-way, radio frequency (RF) power combiners and dividers (splitters) are important components of rapidly developing high power RF and microwave systems used in radars, communication, directed energy, electronic warfare, air traffic control, and scientific facilities such as particle accelerators. Several 21-way L-band combiner configurations of a reactive-radial type with enlarged bandwidth, reduced dimensions for high power applications are analyzed numerically: with smooth air gap, solid dielectric filling, and air gap with wiggling radial walls. The last example employs slow waves enabling size reduction and offers significant increase of bandwidth up to an octave and above at low insertion losses.

1. Introduction

Solid-state Radio Frequency (RF) amplifiers revolutionized both RF and microwave high power technologies for industrial, research, defense, and space exploration applications including long range space RF communications. Middle and high power vacuum devices, such as magnetrons, klystrons, traveling wave tubes (TWTs), and inductive output tubes (IOTs), have been traditionally used, in both pulsed and CW modes. Despite of ubiquitous use of high-power vacuum tubes, there are a number of disadvantages compared to Solid State sources: high voltage (HV) power supplies increases the size, complexity, and weight; it is subject to arcing and significantly limits reliability and safety, and it is sensitive to aggressive environment conditions (humidity, temperature, dust, corrosion). The cathode and filament systems limit the lifetime of vacuum tubes. Tubes usually require a considerable time for filament preheating, thus they cannot be switched on immediately, and, in a quasi-pulsed mode, the filament must remain on, greatly reducing power efficiency. The noise is substantial in vacuum devices as they use thermionic emission having inherent statistical noise in the electron beam. The shrinking market of the tubes (most of which were developed in 60s and 70s) across the world is reducing the production base of vacuum devices, imposing higher long-term risks and growing production cost (unlike solid-state devices) as the technological base narrows. Tubes, and especially TWTs, are also sensitive to vibrations, which is critical in many industrial, space and defense applications.

One of the approaches applied to partially mitigate the problems of vacuum tubes is to integrate a solid-state preamplifier and TWT amplifier in a single module called a microwave power module (MPM). L3 Communications has applied MPMs for Unmanned Aerial Vehicles (UAV) communications [1].

Combining is acknowledged as the key technology for attaining high power in a solid-state device especially in a broad band [2]. We outline here multi-way (>15), in-phase radial structures [3,4] that are usually rather effective in HF-X bands with insertion losses typically less than 0.3 dB and bandwidths <20% (for RF and microwave bands) [5]. Note classical radial combiners of a "mushroom" shape [6,7,8] usually contain a rather small local air gap resulting from impedance transformation. Potential issues related to the narrowed gap may impose more stringent fabrication and assembling tolerances, lower limits on maximum power and/or bandwidth.

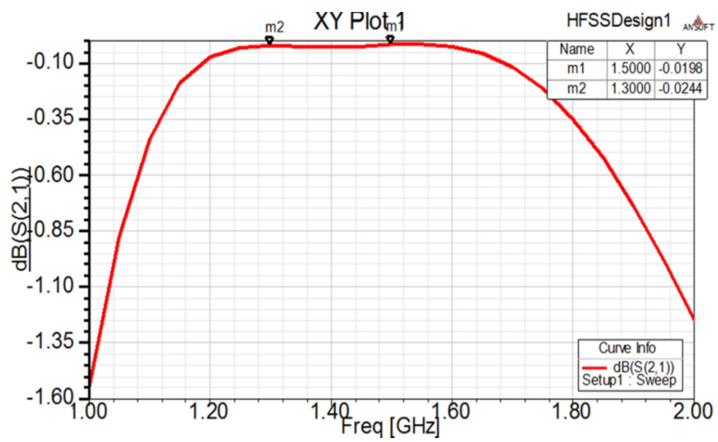
Below we consider several electromagnetic designs for a 21-way L-band combiner of reactive-radial type tailoring substantial bandwidth and power handling, reasonably low losses and reduced dimensions. Most of EM design simulations have been performed with HFSS software from Ansoft [9] for 1/21th sector of the design. Some of the designs were modeled without using the 21-way symmetry using CST Studio Suite™ [10] for imbalance control or thermal simulations. Air gaps are assumed to be everywhere at normal conditions (atmospheric pressure p=1760 Torr). For most of the designs we assume by default 1-5/7" EIA-type central port and 21×N-type peripheral ports to handle at least 4 kW CW output (combined) power.

2. Radial combiners of arc and "bottle" types with smooth air gap

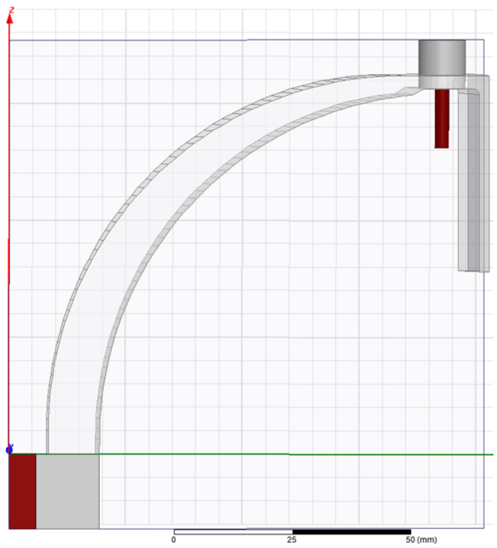
A 21-way L-band divider have been designed and tested [11,12] for CW 8 kW klystron replacement [13]. The arc-radial type divider employs SMA type connectors for peripheral ports and N-type connector for central port. One useful feature of that design is adiabatically smooth tapered radial gap (i.e. without a bottleneck gap between the central coax and radial transmission line of the "mushroom" periphery). Therefore, for initial design of the radial combiner we adopted the same arc type combiner having smoothly tapered air gap.

The air-gap design of the optimized arc type combiner and its S-parameters are given in Fig. 1. The design provides about 60% bandwidth at 0.5 dB insertion loss. Since the gap in the vicinity of the central port remains large (~11 mm) the corresponding fd parameter is 16.5 mm·GHz. Since another breakdown parameter pλ is $3.5 \cdot 10^4$ Torr·mm the ionization power limit will approach ~10^4 W [14], which is about twice the CW power limit for the EIA 1-5/8" connector (~4.5 kW at 1.5 GHz). For the periphery ports the air gap is 2.81 mm in the vicinity of the Teflon insulator of the bulk head mount of N-type connector. That gap corresponds to the fd parameter 4.2 mm·GHz. According to the breakdown curves [14] that imposes again as high as ~10^4 W power limit exceeding by more than an order the power limit for N-type connector (~900 W at 1.5 GHz) and ~200 W anticipated input power per port.

a)



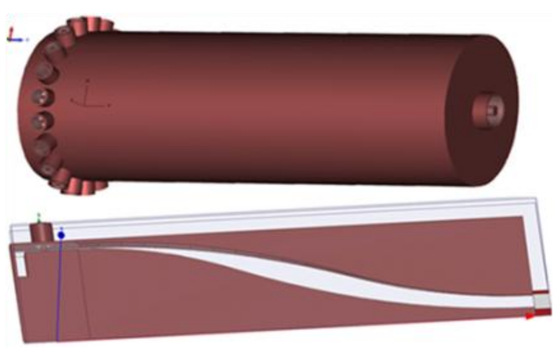
c)



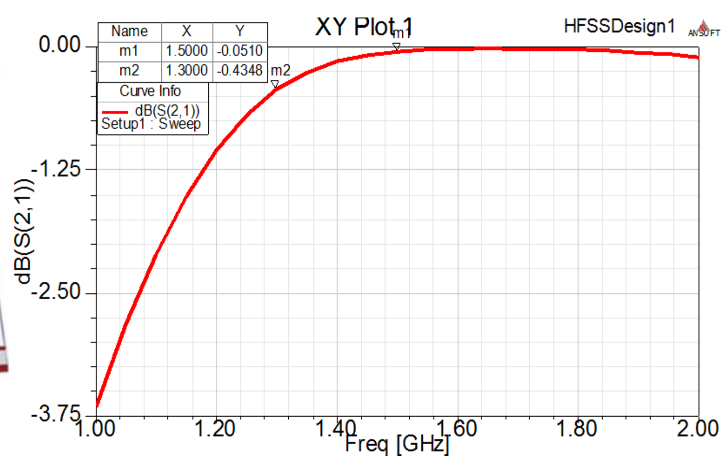
b)

Fig. 1. 21-way arc-type combiner designed for 1.5 GHz frequency, N-type inputs, and EIA-1-5/8-type central output port: "negative" volume view with solids of the 50 Ω coaxial ports (a); Model view for 1/21th sector (b); Insertion loss as a function of frequency (c) simulated for the 1/21th sector (c). The model diameter is 206 mm and height is 104 mm.

We have also considered here another variant of a broadband radial combiner (or divider) with adiabatically smooth air gap. A "bottle" type configuration illustrated in Fig. 2 applies Klopfenstein matching [15] and enables ~44% bandwidth.



a)



b)

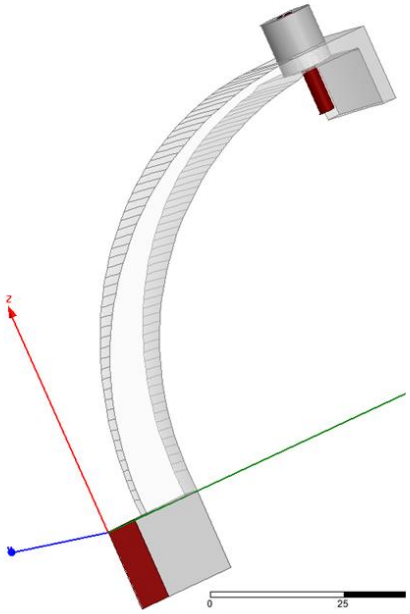
Fig. 2. "Bottle" type 21-way divider having SMA peripheral ports, N-type central port (a) and insertion loss as a function of frequency (b). The model length is ~125 mm.

Both configurations above offer substantial bandwidths and comparable power handling capability due to close i/o air gaps (if adapted to the same connectors). However, substantial dimensions of the designs can present a problem for applications with tight packaging (e.g., for klystron replacement).

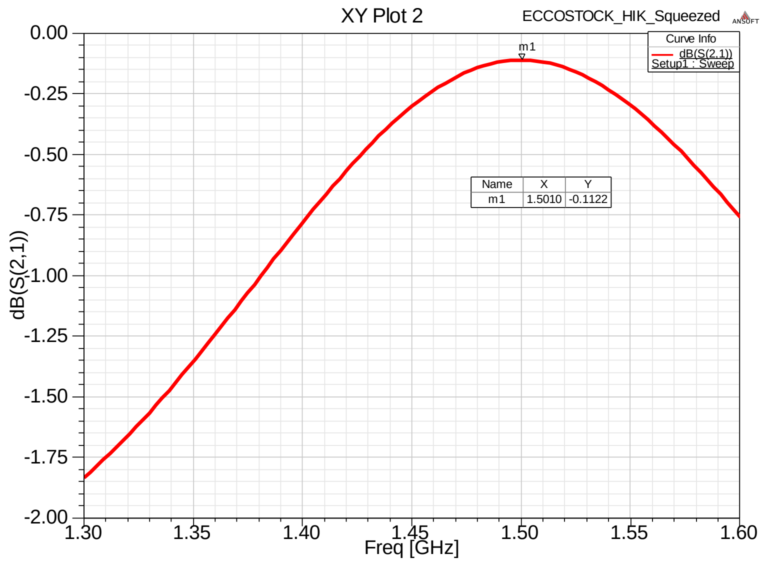
3. Radial-arc combiner with solid dielectric filling

Dielectric filling allows reducing dimensions of the combiner. We found that dielectric constant ε in the range of ~4-6 and loss tangent tanσ less than 0.002 would be about optimal to provide ample size reduction while keeping satisfactory matching, bandwidth and efficiency. A wide range of different materials have been considered including liquid dielectrics. Important additional requirements are low cost, thermal conductivity, maximum operating temperature, spread in dielectric constants, and machinability (for solid dielectrics).

For example, low loss plastic Eccostock®HIK [16] is an attractive option for that filling. The correspondingly optimized design is shown in Fig. 3a,b. One can see from Fig. 3c simulation that the design exhibits rather narrow bandwidth ~10%. However, most serious problem is the high temperature induced by the RF power in the dielectric. The maximum temperature occurring inside the dielectric is 174°C with air cooling and 166°C with enforced water cooling of the metal enclosure (see Fig. 3d,e respectively). These temperatures exceed the 110°C - maximum operating temperature for the material.


z
0
25

a)


XY Plot 2
ECCOSTOCK_HIK_Squeezed
Curve Info
dB(S(2,1))
Setup1 : Sweep
m1
Name X Y
m1 1.5010 -0.1122
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
dB(S(2,1))
1.30
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1.40
1.45
1.50
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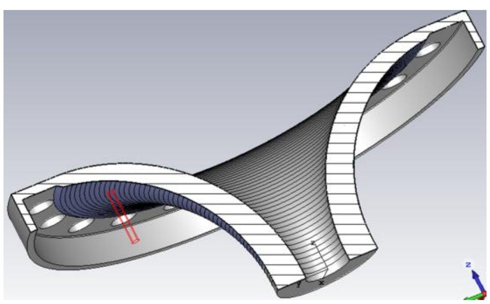
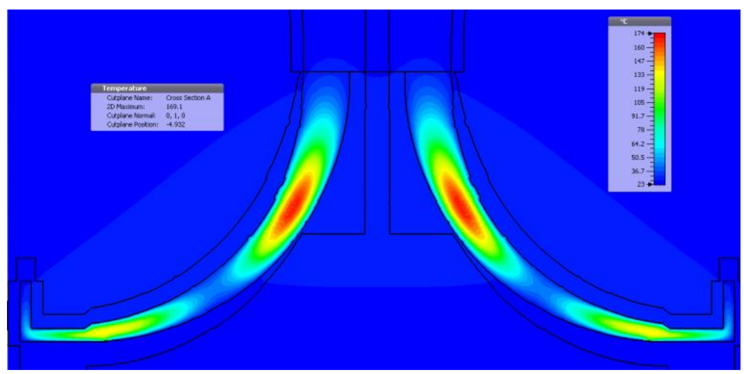
1.60
Freq [GHz]

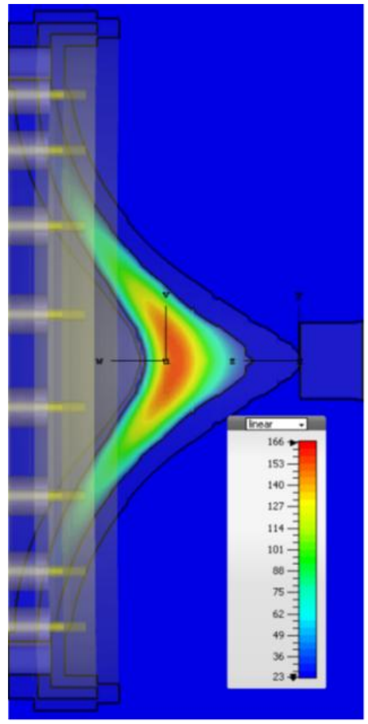
c)



b)


Temperature
174
160
147
133
119
105
91.7
78
64.2
50.5
36.7
23

d)



e)

Fig. 3. Combiner model of $1/21^{th}$ sector with total (transparent) filling of all gaps with Eccostock®HIK (a) and the dielectric cut view (b). Insertion loss simulated as a function of frequency (c). Cut-views of thermal maps simulated for air cooling (d) and enforced water cooling (e). The model diameter is ~174 mm, height is 93 mm. ε=4.37, tanσ= 0.002.

Material review led us to boron nitride (BN) ceramic as the viable compromise between the multiple requirements above. The maximum operating temperature of BN is 1150°C (machinable grade CA in inert atmosphere [17]), and about 850°C in air. That enables high power operation without damage. Optimized design with BN filling of the curved space between the arcs is shown and characterized in Fig. 4.

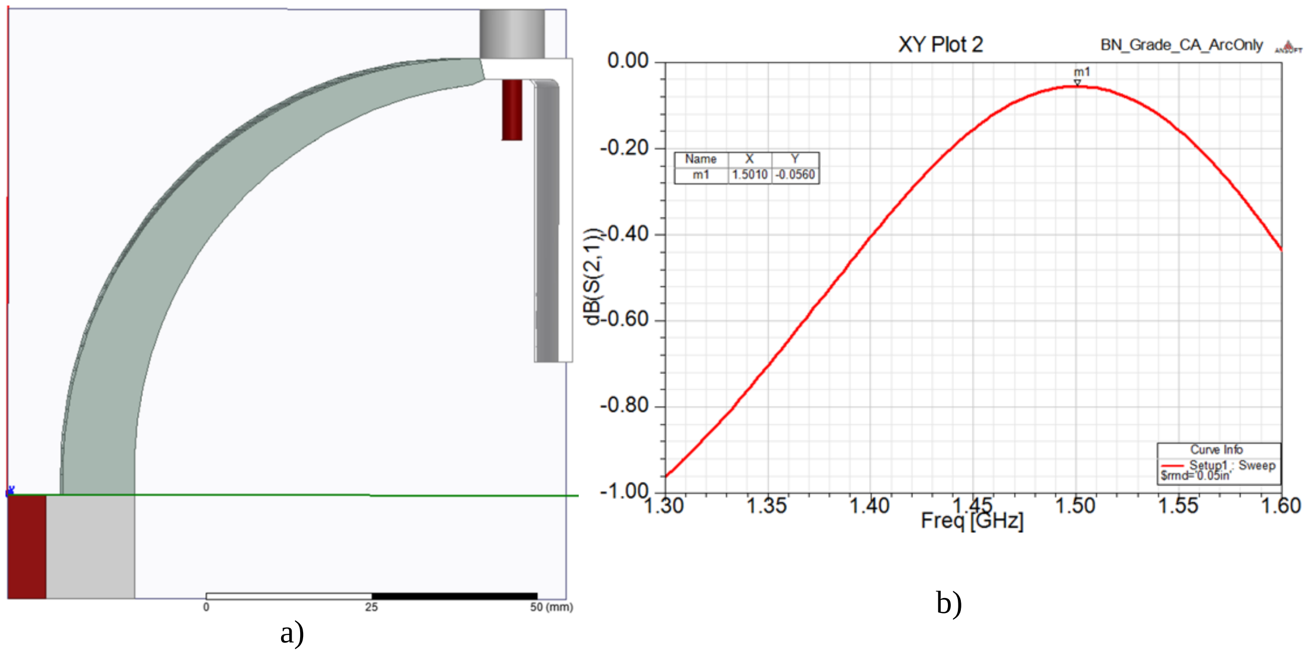


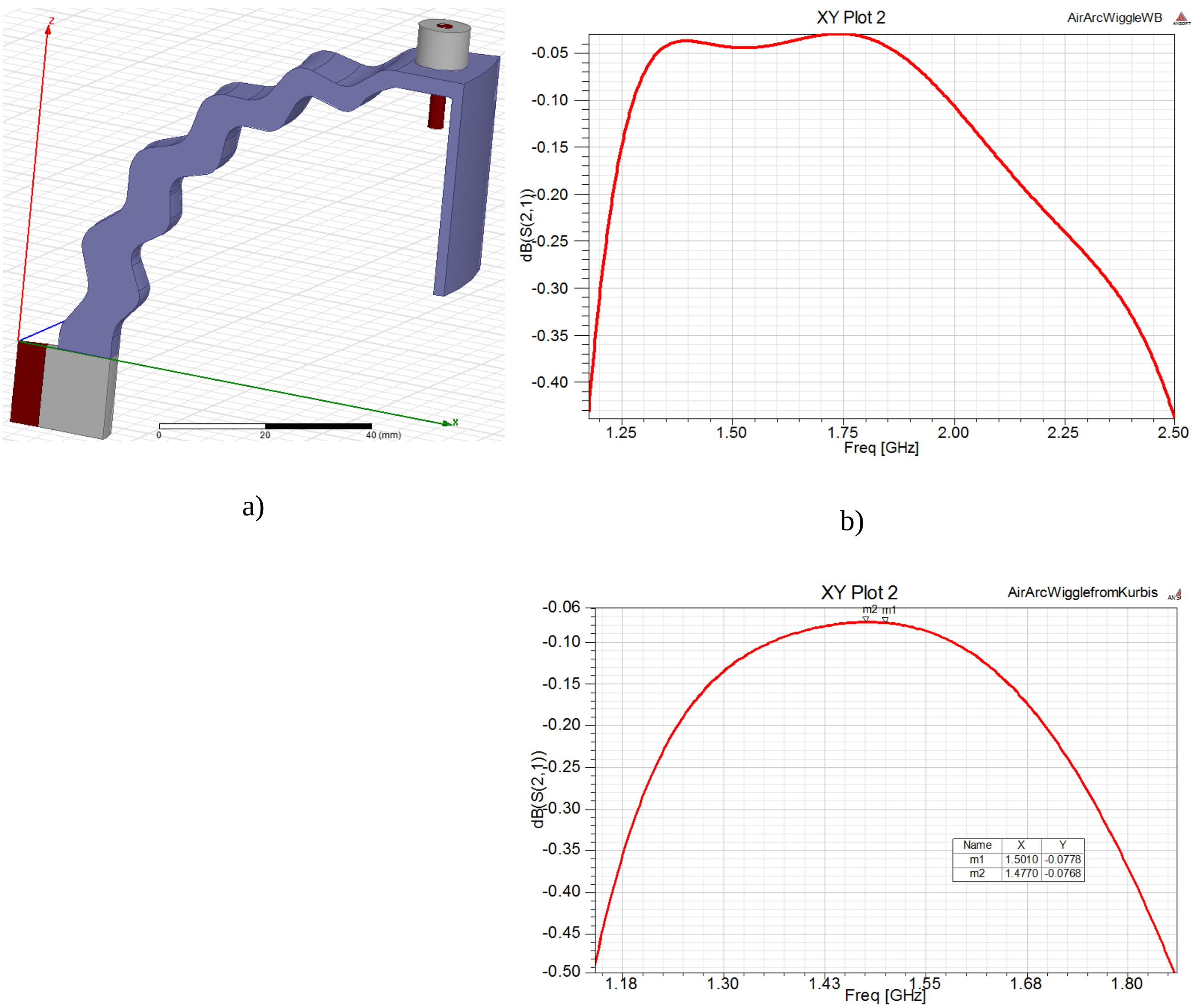
Fig. 4. Combiner model of 1/21th sector with BN filling of the curved space between arcs (green-gray colour) (a) and insertion loss simulated as a function of frequency (b). The model diameter is ~173 mm, height is 90 mm. The main axis of anisotropic boron nitride is oriented along the OZ symmetry axis, ε=(4, 4, 4.3), tanσ=(0.0007, 0.0007, 0.0014), and corresponds to BN Grade CA [17].

One can see from Fig. 4 that the average sizes are reduced in that design by ~ 18% with respect to the air gap design of Fig. 1. However, this is achieved at expense of narrower bandwidth: ~15% at 0.5 dB insertion loss.

4. Wiggling arc combiner with air gap

Using of dielectrics as bulk filling of combiner coaxial gap may have a number of issues: elevated insertion loss, dielectric damage by RF heating, uncertainty in dielectric constant resulting in frequency detuning, increased engineering and mechanical complexity, elevated temperature and/or humidity sensitivity, and increased cost. Besides, the filling resulted in bandwidth reduction of the design above by factor of four.

In Fig. 5a we introduce a novel design without dielectric filling, but employing wiggling radius of the arcs instead serving as a slow wave structure (similar to folded waveguide). One can see from Fig. 5b that the design provides ~76% bandwidth at 0.5 dB insertion loss (i.e. over an octave) at almost the same dimensions as the dielectric filled design of Fig. 4. The bandwidth and shape of the S21 transmission characteristic (see Fig. 5c) is controlled by amplitude and period of periodic modulation of the wiggling radius and the short stub length.



a) b) c)

Fig. 5. Combiner model of 1/21th sector with radially wiggling air gap between the arcs (a) and insertion loss simulated as a function of frequency at different parameters (b,c). The model diameter is ~173 mm, height is ~98 mm.

5. Discussion

The configurations considered here can be applied to designing of RF power combiners and dividers (splitters) which are important components of rapidly developing high power RF and microwave systems used in radars, communication, directed energy, electronic warfare, and air traffic control.

Scientific facilities and especially particle accelerators, operating usually in a narrowband to power high-Q accelerating cavities, do not require wide bandwidth: resonant (or cavity) type of combiners can be used instead. However, in that case tuning is usually required unlike the robust combiners above. Besides, these narrow band combiners and corresponding solid state amplifier systems employing such combiners cannot be applied for other applications operating, e.g., at other (e.g., industrial) frequencies or in a broader frequency range. Therefore using of broadband combiners and dividers in a versatile system may offer much more viable economical solution specially in massive replacing of tubes (e.g., klystrons) operating in a broader band.

Among the wide band applications where such a combiner can be potentially used are also broadcast industry, satellite links, ground penetrating radars, counter-electronic test facilities, and microwave processing using, e.g., variable frequency microwave (VFM™) technology [18].

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