

On the power handling of a high power combiner for industrial, scientific, and medical applications

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Abstract: In this paper a 2-way broadband power combiner that can handle up to 1 kW output power is designed and fabricated. The combiner covers the frequency range of 30 to 500 MHz, which is intended for industrial, scientific, and medical (ISM) applications. The power handling of the power combiner depends on the power handling of the components that constitute the combiner. The combiner is composed of some coaxial transmission lines and a transmission line transformer. The ferrite cores, which are used to suppress the common mode current, are one of the major limiting factors, regarding the power handling of the combiner. The power combiner is implemented with some binuclear and some stacked toroids of material 61, which is extensively used for common mode current suppression in this frequency range. As real ferrites have complex permeability, some of the input power dissipates as heat in the ferrite cores. The power dissipation due to the equivalent parallel resistance of each ferrite core is calculated. The proper operation of the high power combiner is verified by simulation of the temperature rise in the ferrite cores due to heat dissipation.

Key words: Power combiner, broadband, transmission line transformer, ferrite core, power handling

1. Introduction

Broadband power combiners are widely used in high power amplifiers and transmitters. Their power handling and bandwidth determine the bandwidth and restrict the output power of transmitters. At microwave frequencies, high power amplifiers can be constructed by spatial power combining techniques [1]. This kind of power combiner is a mechanical structure with multiple input ports. The power amplifiers are symmetrically placed in space around the combiner. The tuning of individual amplifiers is impossible in this arrangement, because of the spatial distribution of the power amplifier modules. The amplitude and phase mismatch of each amplifier can degrade the combiner efficiency [2]. On the other hand, spatial power combining techniques suffer from poor isolation between the input ports. If one of the power amplifiers fails, lack of isolation results in the malfunction of the whole power amplifiers.

Some planar techniques for inphase power combining use a combination of the Wilkinson and Gysel structure [3]. These combiners are used from VHF through the microwave frequency range. The bandwidth is mostly limited to one octave [3,4]. The isolation between the input ports is achieved either by some floating isolation resistors or some resistive terminations. Regarding the bandwidth and power handling, this kind of power combiner is superior compared to the classical Wilkinson power combiners.

The bandwidth of classical Wilkinson power dividers is increased by multisectioning the divider. Instead of

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the standard 100 ohm isolation resistor used in the classical design, each section will have a different nonstandard resistor [5]. The wide variety of nonstandard valued isolation resistors used in multisection Wilkinson power combiners makes this kind of planar combiner unattractive for high power applications.

Multisection Wilkinson power dividers or combiners are rarely used in multioctave broadband applications that cover the VHF and UHF frequencies, because the dimensions become enormously large. Most reported planar power combiners in the VHF and UHF frequencies have maximum one octave bandwidth [6].

There are some broadband combiners that are a combination of transmission line transformers and some transmission lines, connected in series or parallel [7]. These kinds of combiners and transformers are used in the HF through UHF frequency range. Some transmission line power combiners can be found in patents [8]. There is little information about the theory behind the design of these combiners. For RF engineers working in the high power industry, the power capability and the bandwidth of a combiner are of paramount importance.

In this paper a high power combiner in the VHF and UHF frequency range that is intended to withstand 1 kW continuous wave (CW) power is designed and fabricated. The power combiner consists of a transmission line power combiner with 50 ohm impedance at the input ports and 25 ohm impedance at the summing port, and a 1:2 transmission line transformer to transform the 25 ohm impedance to 50 ohms. All multioctave transmission line transformers and transmission line power combiners use ferrite materials for unwanted common mode current suppression [9]. In the normal operating mode of a cable or transmission line, if a current exists in the inner conductor an oppositely directed current of the same amount must exist in the shield. This is referred to as differential mode current. Any imbalance in the current is equivalent to the coexistence of differential mode and common mode currents in the transmission line. If the cable is wound around a ferrite toroid or if a ferrite slab is used to surround the cable, the common mode current is suppressed by the high impedance induced by the ferrites, whereas the differential mode current is unaffected. Coaxial cables with pure differential mode currents are the key components in transmission line transformers and transmission line combiners.

Ferrites are magnetic materials that have complex permeability [10]. The inductance induced in a coaxial cable for the common mode current is proportional to the real part of the complex permeability. The imaginary part of the permeability is responsible for the power loss in the ferrite core. The power loss in a matched transmission line transformer is mainly due to the conductor and the dielectric loss of the cable and resistive loss of the surrounding ferrite. In most applications, the loss in the ferrite is dominant and must be reduced. Power dissipation in the ferrite reduces the overall efficiency of the power combiner. Proportional to the efficiency degradation, the insertion loss of the power combiner increases and the power at the summing port decreases.

Ferrites are also subject to overheating due to power dissipation. The real part of the permeability decreases with temperature and unwanted common mode currents appear in the transmission lines, which can degrade the performance of the power combiner progressively until an enormous power loss in the power combiner makes it inoperative.

In this paper the power handling of a wideband transmission line power combiner is studied, regarding the complex permeability of the ferrite used for common mode current blocking. To the best knowledge of the author, there is no comprehensive study of power handling for transmission line power combiners. In this paper the loss in the ferrite due to the complex permeability and its effect on the performance of the power combiner are thoroughly studied.

2. High power broadband 2-way power combiner

The schematic of a widely used broadband power combiner for the VHF and UHF frequency range is shown in Figure 1. It consists of a transmission line combiner and a step-up 1:2 impedance transformer. In high power applications, high power flange mount resistors are used as the resistors as shown in Figure 1. These resistors absorb some of the input power into the combiner if one of the power amplifiers connected to the input ports fails. On the other hand, the input ports of the power combiner are isolated from each other and any mismatch between the amplifiers connected to the input ports is absorbed by the isolation resistors.

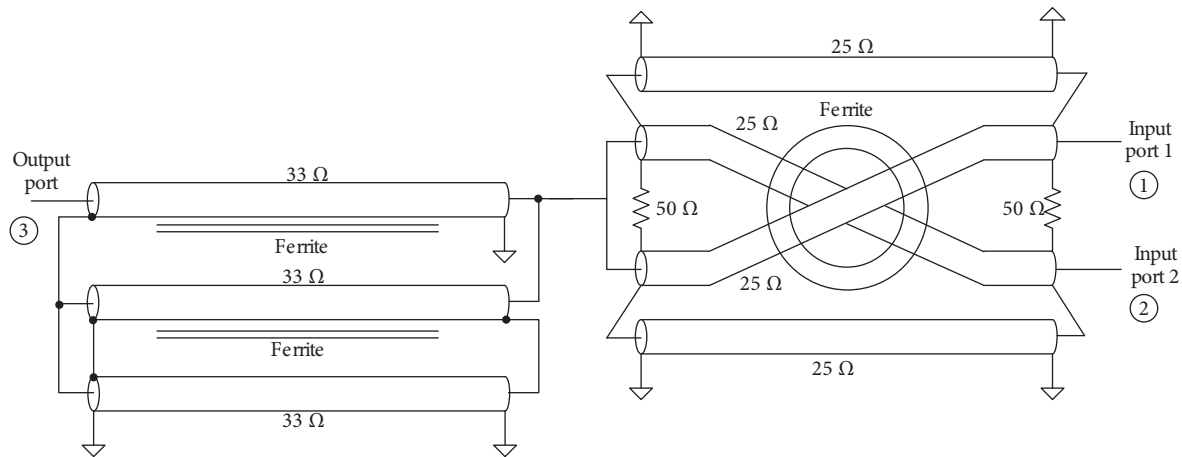


Figure 1. Schematic of the broadband power combiner.

The inner cables of the combing section are crossed and wound around a ferrite toroid. In normal operating mode, the flux in the core is canceled because the magnetic flux density induced by each of the crossed cables is oppositely directed with respect to the other one. Although the presence of the ferrite toroid seems superfluous in the normal operating case, the toroid should not be omitted. In the case of malfunction of any amplifiers connected to the input ports of the power combiner, unwanted common mode currents can flow due to the appearance of a longitudinal voltage in the cables.

Figure 2 shows the direction of current flow and voltages in the cables of the summing transmission line combiner for normal operating condition. As can be seen, there is no current in resistors and consequently no power dissipation. The two input ports of the power combiner are matched to 50 ohms and the impedance of the summing port is 25 ohms. This condition forces the ratio of the voltage to current in the cables to be 25 ohms, which is equivalent to a characteristic impedance of 25 ohms for the cables. The differential mode current flow in the cables together with the previous condition and the way the cables are connected results in proper operation of the combiner. As is evident from Figure 2, the cables experience no reflections on the left or right side.

The transmission line transformer shown in Figure 1 is used to step the summing port impedance of the combiner in Figure 2 to 50 ohms. The characteristic impedance of the cables is 35 ohms. For the analysis of this transmission line transformer a voltage of magnitude V and differential mode currents of magnitude I is assumed in the cables, such that V/I equals 35 ohms. The current and voltages in the transmission line transformer are as shown in Figure 3. For a matched transformer, any reflections in the cables should be avoided. Matching is ensured if the magnitude of the voltage-wave in the cable does not change along the cable and if a current-wave entering the cable leaves the cable at the other side without changes in magnitude. The

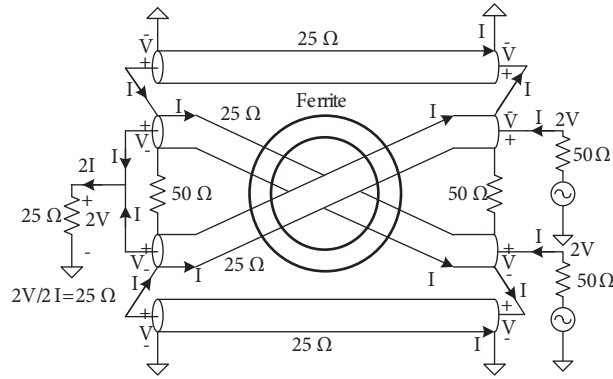


Figure 2. Current and voltages in the summing section of the power combiner under normal operating conditions.

transformation ratio is calculated by the voltage to current ratio at the input port to the voltage to current ratio at the output port. If a voltage along the cable in the longitudinal direction exists, common mode currents are excited. Ferrites are intended for common mode current suppression.

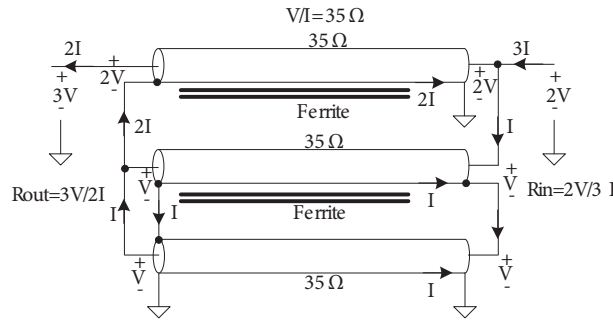


Figure 3. Current and voltages in the transmission line transformer.

The output power and peak voltage at the output in the combiner are given in Eq. (1).

$$P_{out} = \frac{V_{out}^2}{100} \tag{1}$$

For 1 kW output power, 316 V will appear at the output port of the transformer. One third of this voltage appears across the two ferrite cores. Any high frequency voltage along a real ferrite with complex permeability results in power loss and overall efficiency degradation of the power combiner. Power in the ferrite is lost as heat and overheating affects the operation of the ferrite as an unwanted common mode suppressor. The overall effect is reduced power handling capability of the whole power combiner. The impedance transformer and its ferrites are part of the broadband power combiner and so its power handling capability is important for the overall power handling.

The cables used in the construction of the combiner are semi flexible cables with a high quality- low loss dielectric material as polytetrafluoroethylene (PTFE) and with an outer diameter of 0.086” . The RF power is distributed in the cables. Each coaxial cable used in the construction of the transmission line transformer handles up to 350 W at 500 MHz. The power handling of each cable increases with decreasing frequency.

Ferrite components, which are used in the transmission line transformer and summing transmission line combiner, restrict the power capability too. The following section deals with the power loss calculation for

ferrites and focuses on a specific ferrite that is used in transmission line transformers in the VHF and UHF frequency range.

3. Ferrites for high power applications in the VHF and UHF

The ferrite material used for unwanted common mode current suppression is material 61, which is a nickel zinc (NiZn) ferrite developed for high power broadband applications in the VHF through UHF frequencies. The initial permeability of material 61 is 125. Alternatively, it is referred to as material K. The complex permeability of this material is plotted in Figure 4. A wire wound N turns around a ferrite with complex permeability $\mu' + j\mu''$ results in complex impedance given in Eq. (2).

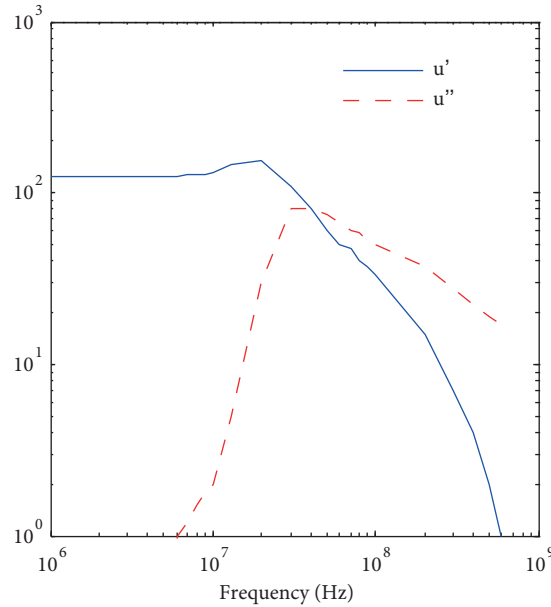


Figure 4. The complex permeability of material 61.

$$Z = \frac{\omega\mu''N^2A}{l} + \frac{j\omega\mu'N^2A}{l} \quad (2)$$

where A is the area of the magnetic core, transverse to the magnetic flux path, and l is the length of the magnetic flux path in the core. The real part of this complex impedance is responsible for power loss and heat dissipation. The factor $\mu'A/l$ is the inductance factor of the core and is equivalent to the inductance of the one-turn coil. The inductance factor is often measured at low frequencies with few turns.

The series impedance can be transformed to an equivalent parallel reactance through the following relations.

$$R_p = \frac{\omega\mu''N^2A}{l} \left(1 + \left(\frac{\mu'}{\mu''} \right)^2 \right) \quad (3)$$

$$X_p = \frac{\omega\mu'N^2A}{l} \left(\frac{1 + \left(\frac{\mu'}{\mu''} \right)^2}{\left(\frac{\mu'}{\mu''} \right)^2} \right), \quad (4)$$

where R_p and X_p are the equivalent parallel resistance and reactance, respectively.

If a voltage V exists across the ferrite core, the power dissipated in the equivalent parallel resistance is

$$P_{diss} = \frac{V^2 l}{2\omega\mu'' N^2 A \left(1 + \left(\frac{\mu'}{\mu''}\right)^2\right)} \quad (5)$$

Another important limiting parameter in the ferrites is the power loss density. The power loss density is the total power loss in the ferrite due to the equivalent parallel resistance divided by the total core volume. The power loss density for material 61 is 350 mW/cm^3 and should not be exceeded for proper operation. There is a tradeoff between the permeability, core dimension, and amount of allowed power dissipation in a ferrite material. Material 61 is in this respect the preferred material for high power broadband applications in the VHF and UHF frequency range.

According to Eq. (5) the power loss for the equivalent parallel resistance of the ferrite depends on the core dimension. Using a ferrite with large volume enhances the power handling of the ferrite core. For the impedance transformer, shown in Figure 3, two binuclear cores of BN-61-002 from Amidon Corp. are used in series. The length of the coaxial cables must be long enough for coiling in the cores. It must be simultaneously be shorter than half wavelength for the highest operating frequency. There is always a transmission line between the shield of the cable and the ground plane of the cables mounted above a continuous ground plane [11]. The presence of a transmission line between the shield and ground plane sets an upper limit for the cable length. For example, a cable that is half wavelength long and is grounded through the shield at one side will be grounded on the other side, through the impedance transformation action of the transmission line between the shield and ground plane. This situation is shown schematically in Figure 5. To avoid these kinds of unwanted impedance loadings, engineers are recommended to use cables not longer than eights of wavelength [12]. In the 1 kW high power combiner, the length of the cables must be long enough for coiling one turn in the two series connected binuclear cores. On the other hand, the cables must be shorter than half wavelength for the maximum operating frequency. The combiner is intended for the frequency range of 30 to 500 MHz and so the cables are chosen to be 13 cm long.

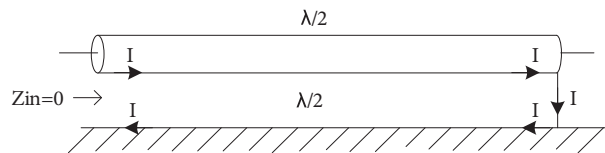


Figure 5. The half wavelength transmission line between the shield of a cable and the ground plane.

The equivalent parallel resistance of a wire wound one turn around two series mounted BN-61-002 ferrite cores has been calculated by Eq. (3) and using the inductance factor of the core. The result is plotted in Figure 6. This resistance appears in parallel to the shield of the cable inside the ferrite core. The power dissipation for 1 kW output power in the two binuclear cores and the resulting power loss density have been calculated by Eq. (5) and plotted in Figure 7. This plot shows that the dissipation in the cores is in the allowed range if the output power does not exceed 1 kW and the frequency is in the range of 30 to 500 MHz. The temperature rise in the ferrite cores is simulated in Solidworks, using the heat transfer analysis tool. The effect of a thin layer of thermal conductive silicone paste between the binuclear ferrite cores and the aluminum case of the combiner is also simulated. The heat conductivity of the silicone adhesive is 1.2 W/mK for the temperature range of $-50 \text{ }^\circ\text{C}$ to $200 \text{ }^\circ\text{C}$. The thickness of the heat conductive adhesive used for pasting the ferrite cores to the aluminum

case is approximately 0.5 mm. The case temperature is set to 80 °C and the power dissipated in a plane inside the cores and parallel to the case is 8.2 W. This number is consistent with the maximum amount of power dissipation, shown in Figure 7.

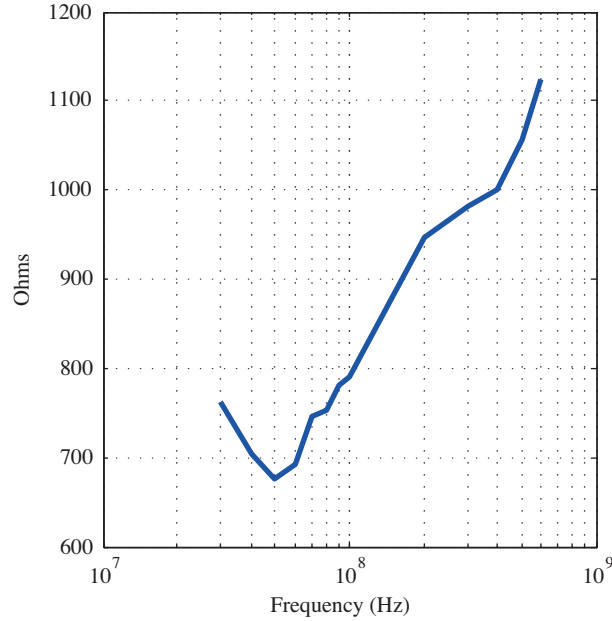


Figure 6. Equivalent parallel resistance of a one-turn coil around two series connected BN-61-002 cores.

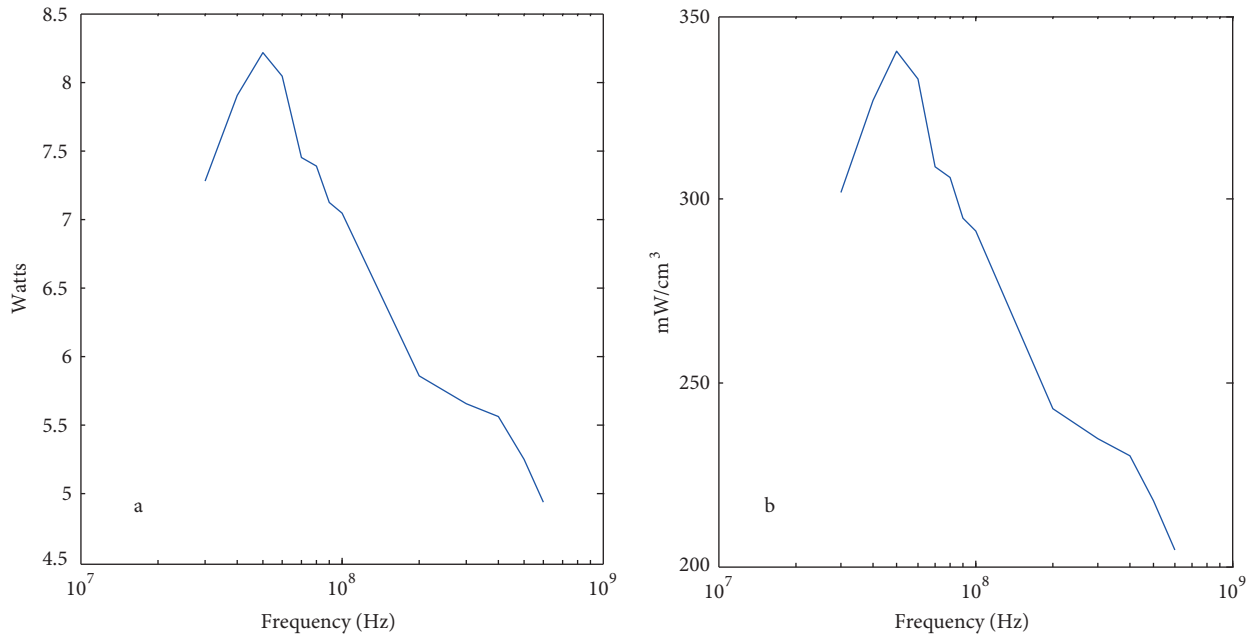


Figure 7. Power loss and power loss density of the two series mounted BN-61-002 for one-turn winding and 1 kW output power. a) Power loss in Watts; b) Power loss density in mW/cm³.

The heat flow is perpendicular to the plane of the case. The thermal conductivity of the NiZn ferrite materials is 35 to 43 mW cm⁻¹ °C⁻¹.

Figure 8 shows the results of thermal simulation. The maximum temperature rise is 118 °C and is far below the Curie temperature of this material, which is 350 °C. In the assembly of the power combiner all ferrite cores are adhered by a thin, heat conductive silicone to the aluminum case of the power combiner.

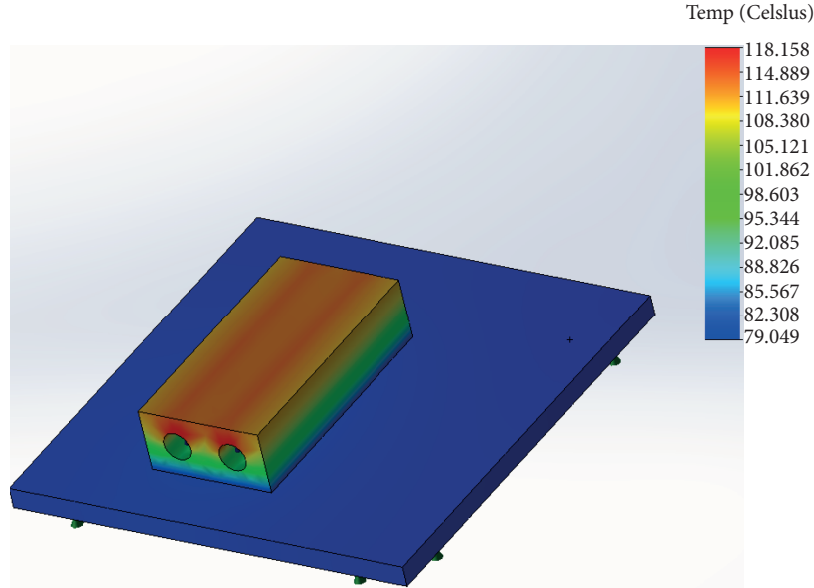


Figure 8. Thermal simulation and heat flow of the two series connected BN-61-002 binuclear ferrites for 8.2 W power dissipation.

4. Power handling of the summing transmission lines

The summing part of the power combiner is shown in Figure 2 and consists of two coaxial cables, which are crossed and wound around a ferrite toroid. For inphase excitation at the input ports of the combiner, the flux in the core is canceled and the toroid seems to be superfluous. The case of one port excitation, which emulates the failure of one of the power amplifiers, is shown schematically in Figure 9.

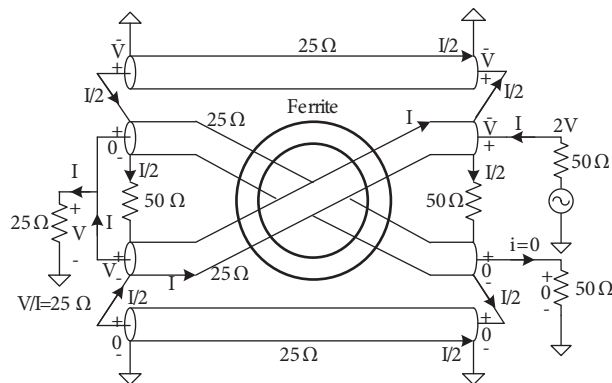


Figure 9. Current and voltages in the summing section of the power combiner in the case of one port excitation.

Power handling is analyzed under this worst case condition. The 500 W applied to the power combiner is divided between the output port and isolation resistors.

For analysis of the combiner under this condition, the other input port is assumed isolated while the excited input and summing ports are matched to 50 and 25 ohms, respectively. The voltage and currents in the isolation resistors reveal 125 W power dissipation in each resistor. For the realization of the power combiner 150 W flange mount resistors from Florida RF Lab are used.

The power handling of the toroid in the summing part can be calculated, similar to the impedance transformer. The voltages along the crossed cables add because they are in series and appear across the toroid. The power loss density of the ferrite core can be increased by stacking four pieces of FT140-61 toroids. The equivalent parallel resistance can be calculated by Eq. (3) and taking account the volume of the stacked toroids. The equivalent voltage across the toroids is 250 V. Using the method outlined in the second part of the paper, the maximum power loss and power loss density are 2.6 W per core and 360 mW/cm³, respectively for the frequency range of 30 to 500 MHz. This power loss density is nearly permissible [10].

5. Fabrication of the 1 kW, 30 to 500 MHz power combiner

The fabricated power combiner is shown in Figure 10. To coil 25 ohm cables through four stacked toroids, the length of the cables is chosen to be 13 cm. Figure 11 shows the magnitude of the measured scattering parameters of the power combiner. In these plots, the ports numbered 1 and 2 are the input ports and the summing port is port 3. The insertion loss of the combiner is 0.65 dB maximum up to 500 MHz and is mainly due to imbalance in the assembly. To connect the output of the summing section of the power combiner to the input of the transmission line transformer, which are both at 25 ohms, two 0.086" diameter, 50 ohm coaxial cables were used in parallel, as shown in Figure 10. This configuration resembles a 25 ohm cable with higher power rating, while symmetry is preserved. To verify the inherent loss of the combiner due to imbalance in the assembly some low power small sized power combiners were assembled. It was surprising that the small signal performance of these combiners does not exceed the large scaled high power combiner.

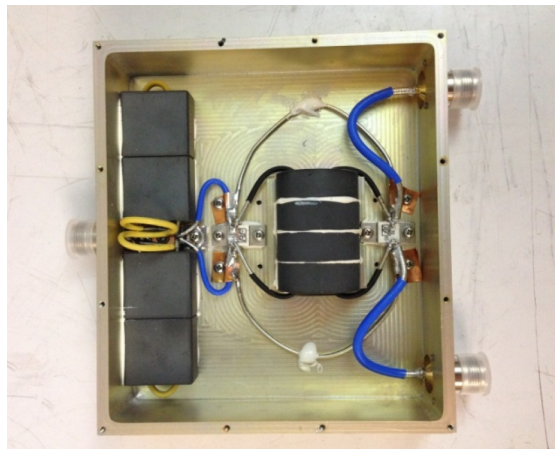


Figure 10. Photo of the fabricated power combiner.

The insertion loss, return loss, and isolation of the fabricated power combiner were measured by a vector network analyzer in the frequency range of 30 to 500 MHz. The insertion loss (S_{13} and S_{23}) and insertion phase difference between the two channels ($\angle S_{13} - \angle S_{23}$) are shown in Figure 11. Figure 12 shows the output return loss (S_{33}), return loss of the input ports (S_{11} and S_{22}), and the isolation between the two input ports (S_{12}), respectively.

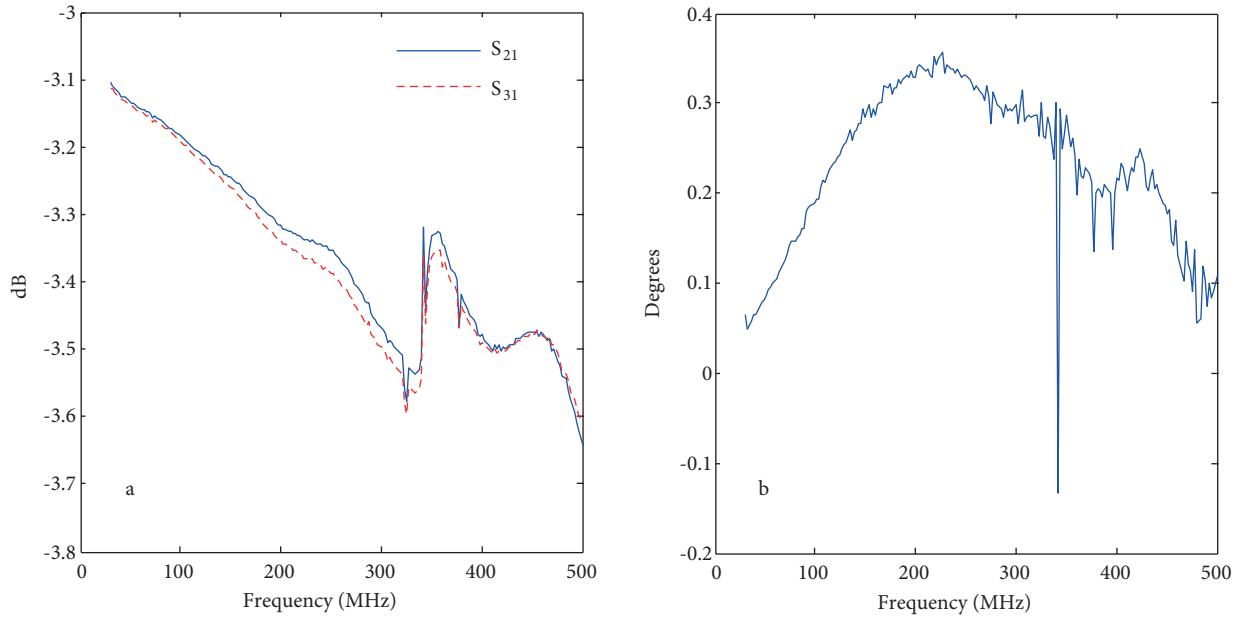


Figure 11. Measured insertion loss and insertion phase difference between the two input channels of the broad band combiner. a) Insertion loss (S_{13} and S_{23}); b) Insertion phase difference ($\angle S_{13} - \angle S_{23}$).

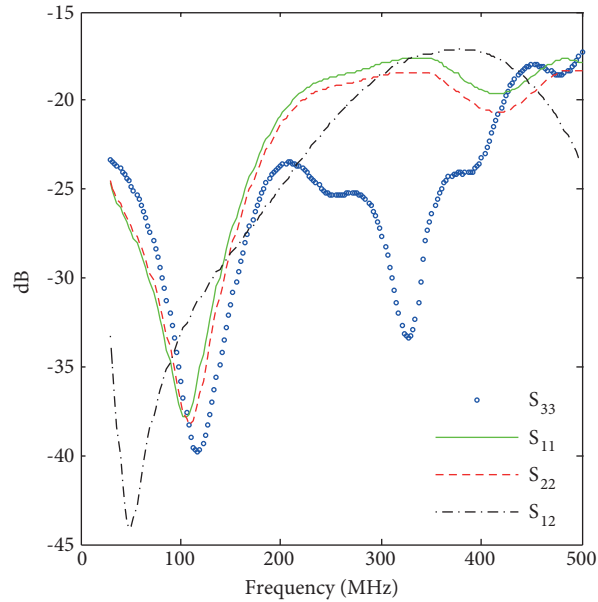


Figure 12. Measured output return loss (S_{33}), return loss of the input ports (S_{11} and S_{22}) and isolation between the two input ports (S_{12}).

The fabricated power combiner as part of a broadband high power transmitter was tested for 1 kW output power. Figure 13 shows the setup for testing the power handling of the fabricated combiner. In this experiment, four broadband 300 W power amplifiers were combined to construct a 1 kW power amplifier. In the last stage the fabricated power combiner was used for power combining. The RF power at the output of the combiner is plotted in Figure 13b. To demonstrate the mismatch between the power amplifiers, the DC current of each

power amplifier is also plotted. In this test, the DC supply voltage was 34 V. There was no sign of malfunction or performance degradation during the tests.

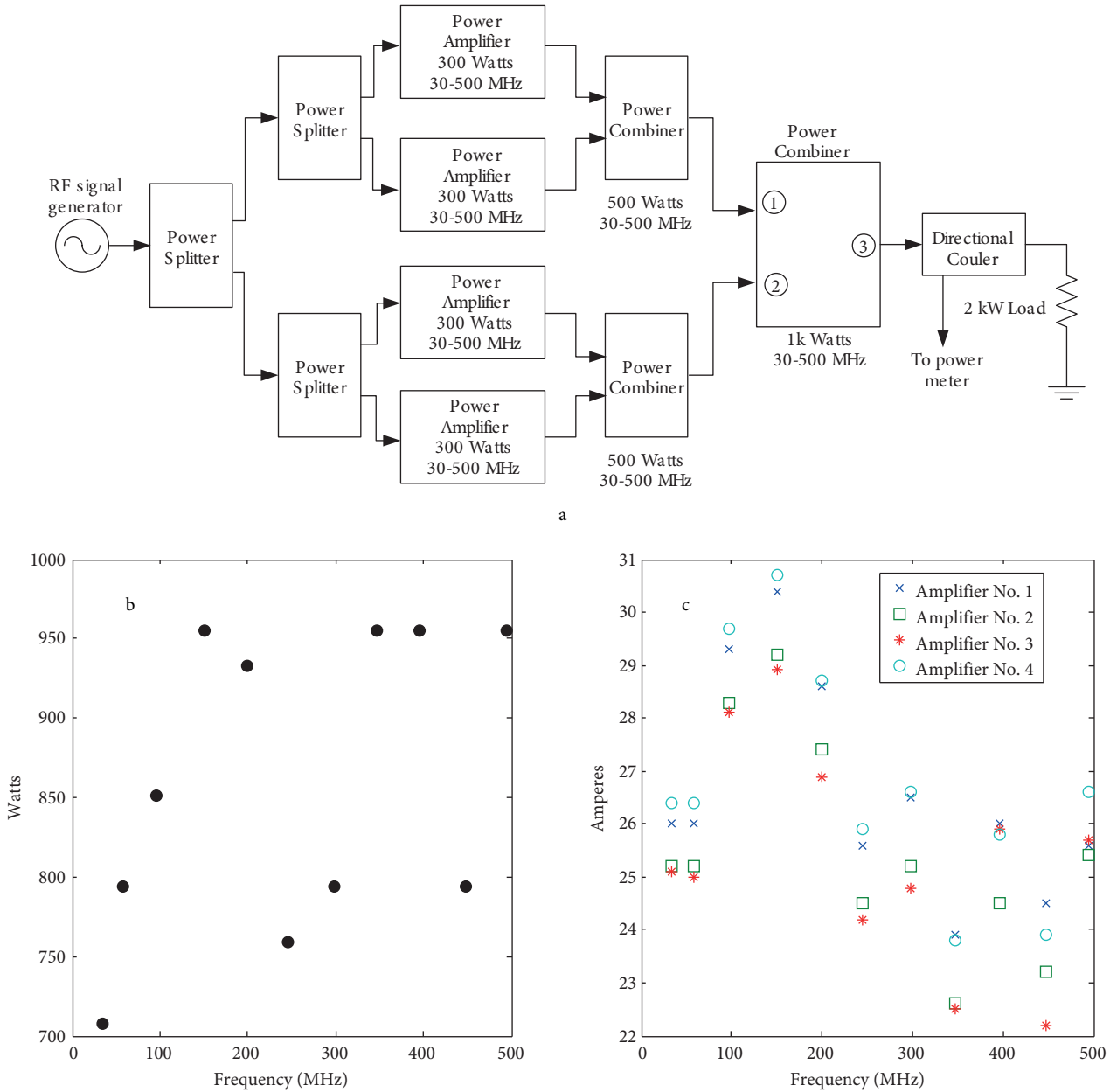


Figure 13. Experimental test to validate the 1 kW power capability of the fabricated combiner. a) Structure of the 1 kW broadband transmitter; b) Output power; c) DC current consumption of each power amplifier.

A direct performance comparison of works is complicated because of different output power levels, frequency ranges, and bandwidth. In spite of all the comparison difficulties, a brief comparison of this work with some other power combiners is given in the Table.

Table. Comparison to other works.

Reference	Structure	Operating freq.	Properties
[1]	8-way radial spatial	7–15 GHz	1 W without isolation resistors
[3]	2-way planar microstrip	660–1340 MHz	Small signal with multivalued surface mount (SMD) isolation resistors
[4]	2-way planar microstrip	4.2–7.9 GHz	Power handling is limited by externally connected termination resistors
[5]	2-way multisection planar	2–10 GHz	Low power multivalued SMD isolation resistors
[6]	2-way planar microstrip	320–660 MHz	Low power SMD components for tuning
[7]	2-way coaxial cable	30–500 MHz	Low power 50 ohm isolation resistors
This work	2-way coaxial cable	30–500 MHz	1000 W with 50 ohm isolation resistors

6. Conclusions

A high power broadband combiner was designed and analyzed thoroughly, regarding power handling and power dissipation. It was shown that ferrite cores used for common mode current suppression limited the power handling of the combiner. The equivalent parallel resistance of the ferrite has been calculated and plotted for the operating frequency range. The power dissipation for the selected cores has been calculated too. It has been shown that the temperature rise due to heat dissipation in the selected ferrite cores was acceptable for 1 kW output power. Stacking large volume binuclear cores and toroidal cores of material 61 increased the power handling of the combiner. The combiner was realized with coaxial cables of 0.085" diameter and a maximum length of 13 cm. Although long coaxial cables were used, no in band resonances have been observed. The amplitude and phase imbalance between the channels of the combiner is negligible. The insertion loss of the power combiner was 0.65 dB maximum and the isolation between the input ports was better than 17 dB for the entire operating frequency range. Actually high power capability is traded off against bandwidth. The proposed power combiner incorporates bulky ferrites in conjunction with long coaxial cables. For high frequency performance, small size cables and small spacing between the interconnections are the basic requirements. The main feature of this work is the layout and mechanical construction of the transmission lines and their interconnections. Any asymmetry in the physical layout and the cable connections can degrade the performance of the combiner. The measured insertion loss (Figure 11), isolation, and return loss (Figure 12) show that the power combiner can operate from 30 to 500 MHz.

There is a trade-off between the bandwidth and power capability (size of the ferrites). In this work, the volume and power handling of the ferrites are calculated analytically and based on some standard ferrite materials and available dimensions a 1 kW power combiner is designed. The fabricated power combiner is suitable for broadband high power applications from 30 to 500 MHz and can handle up to 1 kW output power.

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