When To Use Waveguides Over Coaxial Transmission Lines in RF Applications

White Paper

Abstract

This whitepaper discusses waveguides, coaxial transmission lines, and circumstances where waveguides may be preferred over coaxial transmission lines.

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Introduction

Directing electromagnetic energy in the RF spectrum, from kilohertz to sub-terahertz, along a guided path between two or more nodes efficiently and with some degree of shielding is no easy feat. This challenge of RF interconnect has been tackled in a wide variety of ways that have steadily evolved over the years as electronics and system design has also evolved. However, there have been two mainstays of RF interconnect for decades, which is the venerable waveguide and coaxial transmission line (coax). Though each technology has their strengths and applications they are best suited to, there is a substantial range of applications and use cases where waveguide or coax may be used. These areas tend to be in the extremes of performance or applications with very specific requirements.

Coaxial Transmission Line Primer

Coaxial transmission lines are simply two coaxial conductive surfaces with a dielectric medium in between. The nature of the geometry of the conductive surfaces and dielectric properties of the medium in between allows for the development of a transverse electromagnetic (TEM) mode wavefront that travels parallel to the linear path along the coaxial structure. In this case, the electric component of the wavefront radiates out from the center conductor to the outer conductor and the magnetic field lines circle the center in the space between the center conductor and the outer conductor. With the TEM mode, the electric and magnetic field lines are perpendicular. Though other modes can be developed within a coaxial transmission line, the TEM mode is the most efficient and useful for interconnect purposes for RF applications.

The relative sizes of the center conductor, outer conductor, and dielectric gap between the coaxial conductors dictates key electromagnetic properties of a coaxial transmission line. These properties include the characteristic impedance, maximum frequency of the TEM mode, dielectric breakdown voltage, maximum power handling, loss per unit length, and others. Other factors of how a coaxial transmission line is fabricated, such as tolerances and material properties, also impact the dielectric breakdown voltage, power handling, loss, passive intermodulation distortion (PIM) characteristics, VSWR, return loss, etc.

Coaxial transmission lines are most often fabricated as coaxial cable and coaxial connectors. The coaxial connectors are attached to the coaxial cable to make a complete RF interconnect solution that is readily used to interconnect ports within a device/system or between external device/system ports. Most coaxial cables are made with a center conductor, dielectric spacer, outer conductor, and some type of jacketing to protect and make handling a coaxial cable easier. There are many variations to the materials and structures used to make a coaxial cable, such as flexible or rigid conductors and solid or segmented dielectrics. Also, many coaxial cables are made with additional layers to enhance the properties of the coaxial cable, including environmental protection layers, mechanical performance enhancing layers, and layers specific to enhancing electrical performance criteria.

A coaxial connector is made of a center pin with some method to attach a coaxial cable center conductor and an outer housing with a method for attaching to the outer conductor of a coaxial cable. There are also coaxial connector variants made to attach specifically to circuit boards or as probes that mate to a designed contact structure. Coaxial connectors may be plated or coated to enhance performance and there are several base materials often used as the housing/outer conductor of a coaxial connector, such as brass or stainless steel.

Many RF devices, components, and systems have coaxial ports accessible to allow for ease of interconnect using coaxial cables. Such devices or components are often referred to as “coaxial connectorized” packages or enclosures. Coaxial connectors can also be combined into a single unit, such as an adapter or rigged extension, where the coaxial connector housing is extended, and no coaxial cable is needed. As there are many different standards for coaxial connectors, coaxial adapters are useful for connecting between different coaxial connector types.

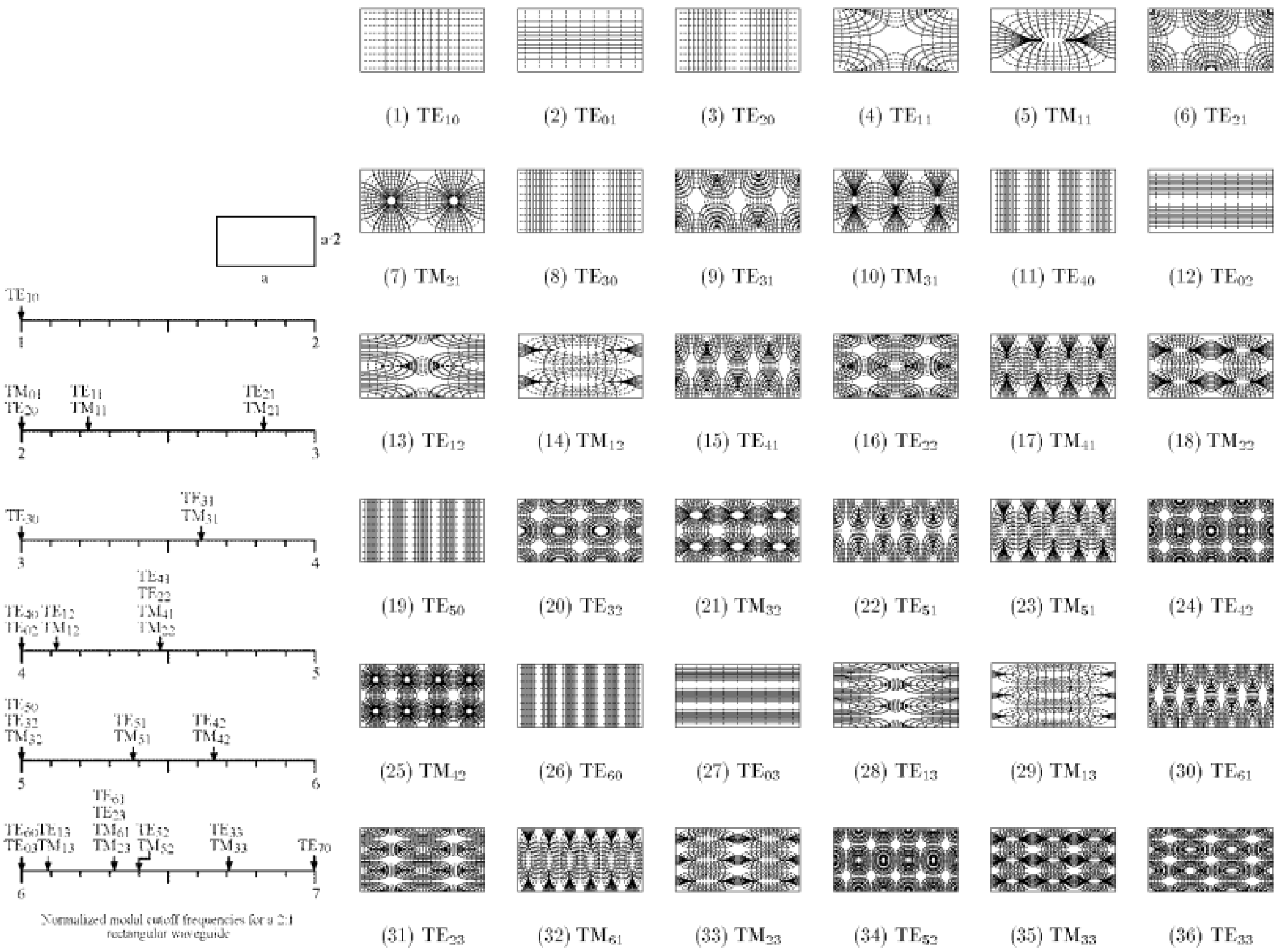
Waveguide Primer

A waveguide is a type of hollow conductive structure with a dielectric medium within it. The 2-dimensional cross section of a waveguide dictates the characteristics of the wavefronts passing through the waveguide. One of several different modes are formed within a waveguide depending on the physical dimensions of the waveguide and the waveguide shape. Typically, a waveguide is designed with a desired primary mode in mind and specified to operate with that mode. For instance, common rectangular waveguides are typically designed to operate with the transverse electric (TE) or a transverse magnetic mode (TM). Waveguides are not able to support a TEM mode. With the TE modes the electric field is perpendicular to the direction of propagation of the wavefront, while with the TM modes, the magnetic field is perpendicular to the direction of propagation. For the TE mode, the magnetic mode is in the direction of propagation, and with the TM mode the electric field is in the direction of propagation. This type of wavefront guidance has an upper and lower frequency limit that directly relates to the internal geometry of the waveguide in relation to the wavelength of the EM signal. Signals within this frequency range effectively reflect within the waveguide along the waveguide path, which makes the internal walls of the waveguide a critical surface for the overall performance of the waveguide structure. This is why the inner walls of waveguides are often plated or coated to ensure a smooth and conformal surface along the length of the waveguide. These plating’s and coatings are often also used to thwart corrosion, which is why many high-performance applications use a thin gold plating on the inside of the waveguide. Silver, or even copper, would be more ideal conductors from an electrical conductivity perspective, but gold is more corrosion resistant, which is why it is preferred for this application. Waveguides may also have the inner dielectric enclosed with a barrier and sealed to prevent external contaminants from entering the waveguide medium and to prevent environmental degradation.

Waveguides may be rectangular or elliptical, and the shape of the waveguide structure determines what dominant mode is available. Rectangular and circular waveguides are the most common waveguides used in RF applications. The TE10 mode is the dominant mode for rectangular waveguides, as this mode has the lowest maximum cutoff off frequency of the rectangular waveguide modes. With this mode, the electric field lines pass vertically between the two long-walls of the waveguide, while the magnetic field lines loop parallel to the long-wall of the waveguide. Waveguides are typically designed to operate such that only the dominant mode is active, while the other modes are at substantially higher frequencies.

With circular waveguides, the TE11 mode is dominant, where the electric field lines curve from the “top” and “bottom” of the circular waveguide with the magnetic field lines looping and intersecting the electric field lines orthogonally.

(a)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Normalized modal cutoff frequencies for a 2:1 rectangular waveguide
(1) TE_{10}
(2) TE_{01}
(3) TE_{20}
(4) TE_{11}
(5) TM_{11}
(6) TE_{21}
(7) TM_{21}
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(9) TE_{31}
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(b)

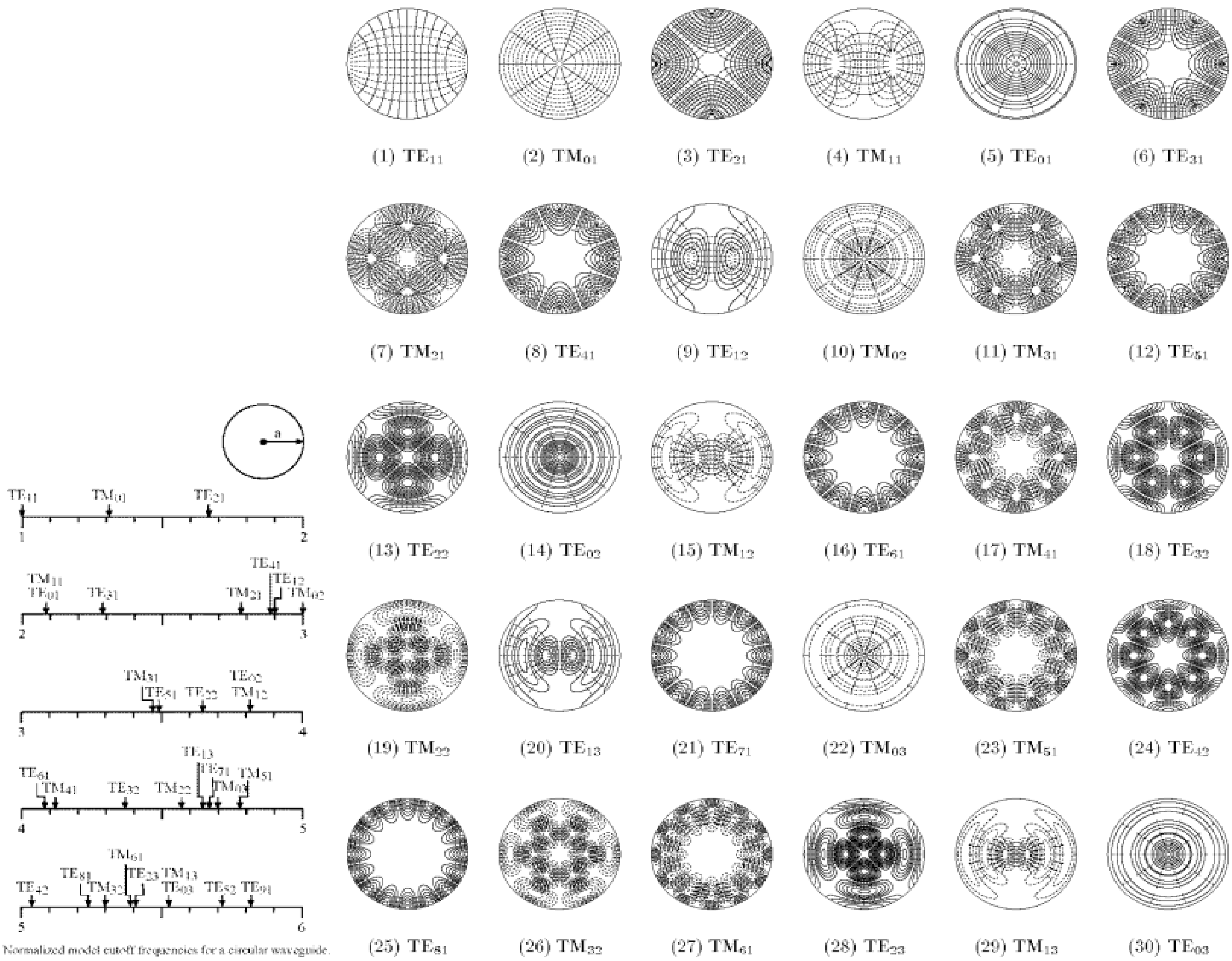

Image: A diagram of the electric and magnetic field lines in common rectangular (a) and magnetic (b) waveguide structures[1].

Most waveguide structures are solid metallic conductor structures with flange style connection plates on either end of the waveguide. These flanges are used to align the waveguide faces such that a continuous waveguide structure is made once the flanges are mated. The alignment and tolerances of the waveguide transition between flanges is critical to the performance of mated waveguides.

Waveguides can be made to be flexible using specialized processes of joining segmented conductive structures with feature sizes far less than the wavelength of the upper frequency limit. There are also waveguide transitions that can be used to transition between TE11 mode rectangular waveguide and TE11 or TE01 mode circular waveguide. These transitions tend to have a limited frequency range and performance. There are also rotary waveguide transitions based on circular waveguides that allows for an uninterrupted circular waveguide environment while the conductive structure spins around the center point. Rotary waveguides are useful for applications that require signal transfer through rotating segments, such as with rotating radar.

Key Electromagnetic Interconnect Properties

In order to compare coaxial and waveguide, it is first important to detail what the key metrics for comparison are. In this case, these metrics are the key metrics for RF interconnect:

Key RF Interconnect Metrics

- Frequency Range (lower frequency limit to upper frequency limit as specified)
- Loss per unit length
- VSWR or SWR
- Voltage breakdown
- Power handling
- Size and weight
- Ease of use/installation and accessibility
- Cost

The electrical performance parameters frequency range, loss per unit length, VSWR, voltage breakdown, and power handling are relatively straightforward. As important as these metrics for many applications are the size and weight of the interconnect, as well as the ease of use/installation and accessibility to the product. Lastly, relative costs will be discussed, though there are many market factors that impact this metric in ways that are difficult to quantify.

Coaxial Transmission Line Strengths

Coaxial cables, connectors, and assemblies have become ubiquitous in RF and wireless applications. Coaxial technology is relatively easy to use with prepared cable and connectors, and the tools and training required to assemble most coaxial technologies is generally accessible. In many cases attaching coaxial connectors to a cable assembly requires simple hand tools and is commonplace to be done in the field by technicians installing and troubleshooting installations.

There are specialized versions of coaxial transmission line technology that do require specialized tools and processes to work with. These specialized coaxial interconnect types are typically designed to overcome some of the basic limitations of coaxial transmission lines and enhance the electrical, mechanical, and environmental performance. Hence, the additional cost and effort of using these coaxial technologies is offset by a performance benefit. For instance, there are special jacketing materials, connector seals, and connector boots that help to enhance the environmental protection of a coaxial technology.
As coaxial technology is so common, there are many types of coaxial connectors and cables designed and rated to operate in use cases and installations that require meeting regulatory codes and standards. An example of this is Plenum rated coaxial cable in the United States. Building codes require materials installed in certain spaces to meet various code requirements, such as fire safety in plenum spaces. Many of the codes have to do with the dielectric material and jacketing material used in the cable assembly process, as the other materials are all metallic conductors.

The most common type of coaxial interconnect is a flexible coaxial cable assembly. These assemblies are based on a flexible coaxial cable with coaxial connector ends. Flexible coaxial assemblies can be ordered in a wide variety of configurations depending on user needs, from low-cost to low-loss. There are also semi-rigid coax and rigid coaxial technologies which exhibit better electrical, mechanical, and environmental performance than flexible coaxial cable assemblies, but at higher cost and less opportunity for reuse or reconfiguration.

The most common and accessible RF test equipment, devices, and components that are not designed for planar circuit technologies are typically coaxial connectorized packages and modules. This means that prototyping, testing, and even deploying RF technology typically involves coaxial interconnect. There are common coaxial connectors that operate to 18 GHz (precision SMA), and others that are relatively widely available that operate to 67 GHz (1.85mm). Additional coaxial connector standards exist that operate to 100 GHz and above, but these are still less accessible than other coaxial connectors standards due to their niche use cases.

Waveguide Strengths

Waveguide interconnect is extremely efficient while operating in the dominant modes, as there is only a low-loss dielectric medium and reflective conductive surface to introduce loss. As a waveguide structure can be entirely made up of conductive metals, these structures can typically handle relatively high power before risking dielectric breakdown or failure from overheating the interconnect.

As the cross-section dimensions of a waveguide directly relate to the operating frequency of the dominant mode of the waveguide, millimeter-wave waveguides can be extremely compact and carry significantly high-power levels with minimal loss. This is partially why waveguides are often used as the interconnect of choice for high performance and high-power applications above 10 GHz.

Waveguides are typically designed to be extremely robust and are generally plated/coated with materials with very high corrosion resistance. Hence, the operational lifespan of waveguide technology can be decades, or even longer, without service. Flexible/formable waveguide and other specialized waveguide technologies typically sacrifice some robustness/reliability and performance for flexibility/formability, but these trade-offs still allow for the waveguide interconnect advantages of low-loss and high-power handling.

Though the waveguide medium is intrinsically banded, there are waveguide variations, such as double-ridged and quad-ridged waveguides, that exhibit extended frequency bands to multiple octaves. Moreover, there are several types of waveguide antenna that are directly compatible with standard waveguide and these extended frequency range variants. These types of waveguide antennas, such as horn antennas, are the universal standards for testing other antennas and probes due to their high antenna efficiency, gain, and directivity.

There are waveguide variants of all major types of RF passive components, such as attenuators, filters, power combiner/dividers, couplers, isolators/circulators, terminations, etc. These variants can be made to operate with extremely low loss, at very high-power levels, and will provide very high-quality factors. Moreover, waveguide technology, with the exception of some open/slotted waveguide types, are intrinsically exceedingly well shielded. This means that waveguide technology is generally very immune to outside interference, and also provides enhanced security and prevents leaking interference.

Coaxial Cables Versus Waveguides

Ultimately, the choice of using waveguides or coaxial transmission lines comes down too many system or device/component design factors and possibly even customer requirements. There are many legacy systems, such as radar, that were originally designed with waveguide interconnects that would require excessive redesign to accommodate coaxial transmission lines. Many modern AAS are using a multitude of lower power signal paths, which lends themselves more toward coaxial interconnect than waveguide interconnect.

Where waveguides are most likely to be used are scenarios where reducing the loss, conveying high power levels, providing the highest possible interference immunity, and ensuring signal security/minimizing interference generation, are the most significant concerns. Given the relative size of waveguides at lower frequencies, these applications are likely to be in the X-band (8 GHz to 12 GHz) or above. There are applications with lower frequency operating waveguide, but these structures tend to be large and costly, which is why they are generally only found in certain research, military/aerospace, and satellite communication applications.

The relatively high cost of waveguide interconnect compared to coaxial interconnect generally results in coaxial interconnect being preferred for cost sensitive applications. There are lower cost waveguide options, however, these interconnects still tend to be many times the cost of coaxial interconnect, and possibly more considering the need for waveguide-to-coaxial adapters in order to interface with common test equipment and other RF devices/components.

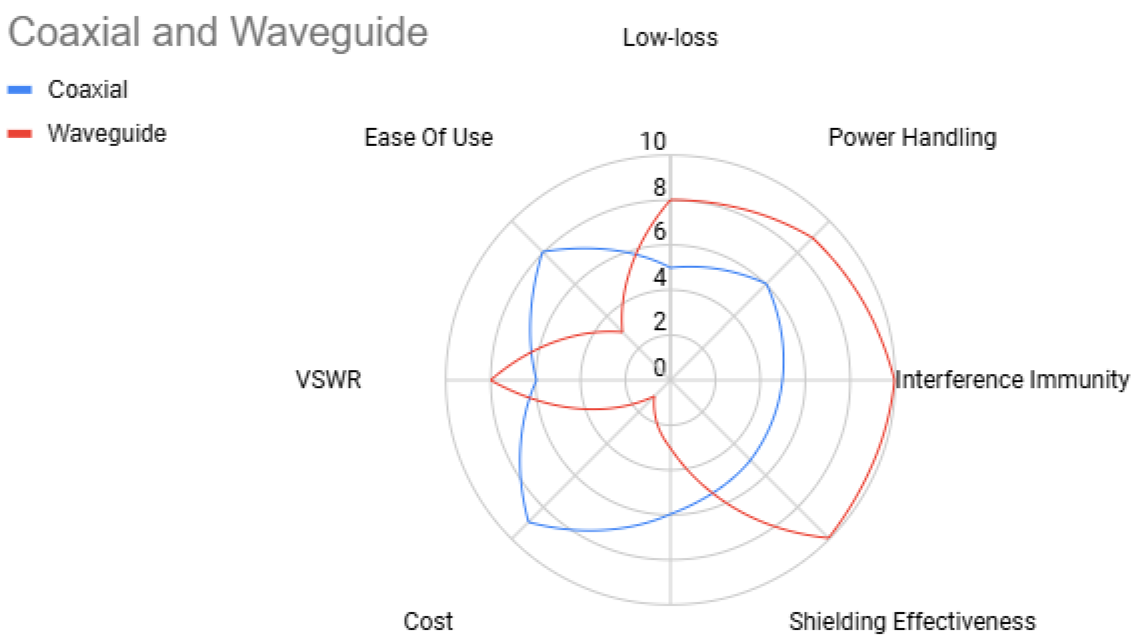

Image: A chart depicting the relative comparison of coaxial transmission lines and waveguides for RF applications.

Coaxial interconnect can operate from DC to the upper cutoff frequency, whereas waveguides have both a lower and upper cutoff frequency. This means for a waveguide to operate over a wide range of frequencies requires several waveguides of different sizes and different signal paths, or the ability to switch out waveguides to match with the desired frequency range. This can pose difficulties in wideband tests where it may be necessary to stitch data together between tests over several waveguide frequency bands. This is one of the reasons why the most common RF test and measurement technology uses coaxial transmission lines and ports.

Rotary systems, however, typically use circular waveguides, at least in the rotary transition, as a rotary coaxial system is much more difficult and costly to implement. If circulatory polarization is needed, circular waveguides are also typically used, though circular polarization is possible with coaxial connectorized antennas as well.

Conclusion

Both coaxial transmission line and waveguide technologies have their place in legacy and the latest RF systems. For non-planar applications above 10 GHz, there can be an option of using coaxial transmission lines or waveguides. Ultimately, the choice breaks down to the nuances of the system requirements, but if power and performance are the priorities, the clear choice is waveguides. When economy, accessibility, and ease-of-use are paramount, then clearly coaxial transmission lines are preferred.

References

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