

Phase Matching and Tracking of Coaxial Cable Sets

Modern approaches to microwave systems have increased the need for phase matched coaxial cable sets. For example, instead of spinning a large radar antenna to generate a radar image, multiple stationary elements are electronically scanned to generate the radar image. Therefore, each element, or group of elements, is fed through a single cable of a phase matched-phase tracking cable set.

Ideally, each cable in the set has precisely the same phase characteristics as every other cable in the set. That is, the designer would like a phase tolerance to be zero. In practice this is not possible and manufacturers offer a tolerance of plus or minus a “proverbial” mile. The cable manufacturer determines a reasonable match tolerance based on several factors, some of which relate to cable materials and construction, cable length, connector interface and operating frequency. While it is almost always possible to get a smaller match tolerance, the trade off is increased manufacturing time and higher cost.

The manufacturer typically performs the phase matching under room ambient conditions with the cables in a standard configuration. The match may remain constant with temperature or, more likely, change with temperature; the same is true for installation bends. Thus, the achieved match depends upon the configuration and temperature uniformity of the system.

In short, the system designer and cable manufacturer must agree on the value placed on the match tolerance and that match limit will most likely require an additional allowance for any phase change after installation in the final application.

Discussion

Let us examine the influence of several parameters on the closeness of the phase match. Although phase match is used throughout this paper, the concepts are the same for time delay matching, phase offsets, etc.

Highest Frequency of Operation

In a given medium the wavelength (λ) is inversely proportional to frequency. At 18 GHz, λ is one eighteenth as long as it is at 1 GHz. From the manufacturer’s viewpoint, it can be 18 times more difficult to achieve a given match at 18 GHz as achieving that same match at 1 GHz.

Connector Construction

A simple connector (see *Figure 1*) soldered directly on to the cable outer conductor is easy to move. By changing the mechanical length, the phase length can readily be adjusted to a tight tolerance. A more complex

design where the outer conductor braid is combed out and clamped over a braid shim is much more difficult to move and make fine adjustments.

SMA CONNECTORS

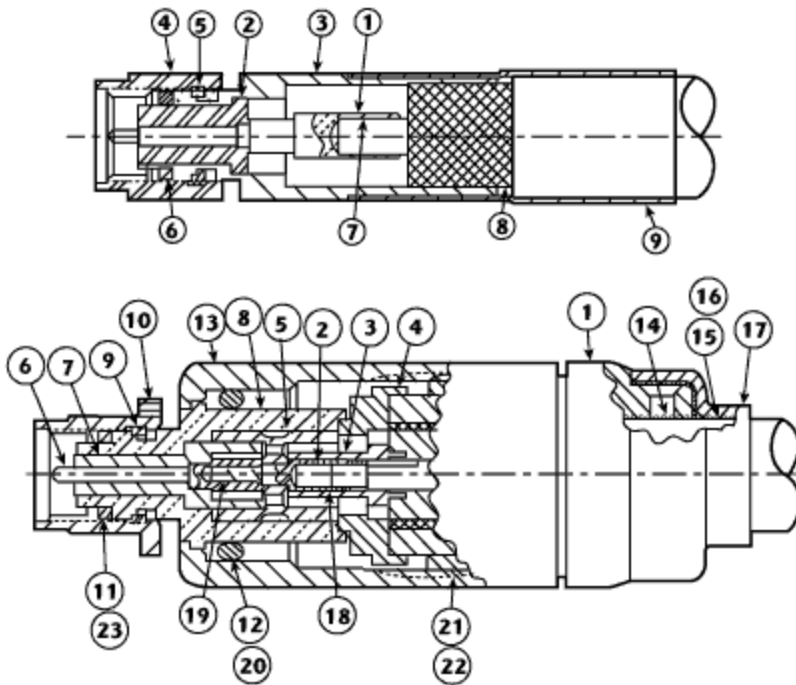


Figure 1 Comparison of a simple general-purpose connector (top) and a complex military connector (bottom).

Variation of Velocity of Propagation (V_p)

To achieve low loss, coaxial cable manufacturers often use air-spaced dielectrics rather than solid dielectrics. If the air/dielectric ratio is not exactly the same throughout the cable run as well as from run to run, there will be variations in V_p . In this case, two cables having precisely the same physical length may have different electrical lengths. Clearly, tight control of V_p eases the phase matching problem and results in assemblies having closer physical lengths.

Consider an example: Suppose we want a set of ten-foot assemblies for use up to 18 GHz. Assume that the V_p of the cable can vary over the range 81.0 to 83.0 percent ($0.81C$ to $0.83C$ where C is the speed of light in free space, approximately 3×10^8 meters/second). Since $\lambda = C/f$ where f is the frequency in Hertz, the free space wavelength at 18 GHz is 0.0167 meters. Within our cable with its nominal V_p of 82 percent the effective wavelength is $\lambda_e = V_p \lambda$ or 0.0137 meters long. Our hypothetical ten-foot cable with a nominal V_p of 82 percent is 223.1 wavelengths long. Each wavelength is a 360 degree phase shift so the electrical length will be around 80,316 degrees.

If we repeat the calculation with V_p reduced to its assumed 81 percent lower limit, the effective wavelength is 0.0135 meters. The same ten-foot cables are now 225.8 wavelengths long with a corresponding phase shift of around 81,288 degrees—not very well matched electrically.

It is instructive to calculate the physical length change required to electrically match the second cable to the first. We need to cut it back to be 223.1 wavelengths long. The amount to remove is 0.0364 meter (1.44 inches). Under our assumed conditions, we require a physical tolerance of ± 1.5 " to achieve our match. While intuition might say use ± 0.12 inches to achieve a good physical match, a tight length restriction only limits the amount of cable that can be used to fabricate the matched cables and does not assure a close electrical match. In fact, as

shown in this example, cables with exactly the same length have a phase variation due to different V_p s of approximately 980° .

Temperature

The electrical length of a coaxial cable with PTFE dielectric changes as a complex function of temperature. Often air is introduced into the PTFE dielectric by foaming or expanding it to increase the V_p and reduce the cable loss. How much air and how this is accomplished is the topic for another article.

Typical phase-temperature characteristics are shown in **Figure 2**. Note that over most temperature ranges the higher V_p cables exhibit smaller phase changes than the lower V_p cables. This is an additional benefit of an air-spaced PTFE dielectric and is also important in phase tracking, which is discussed in the next section. A key observation here is that when fabricating cables of a phase matched set, it is necessary to stabilize the cable and perform all phase matching in a temperature controlled area.

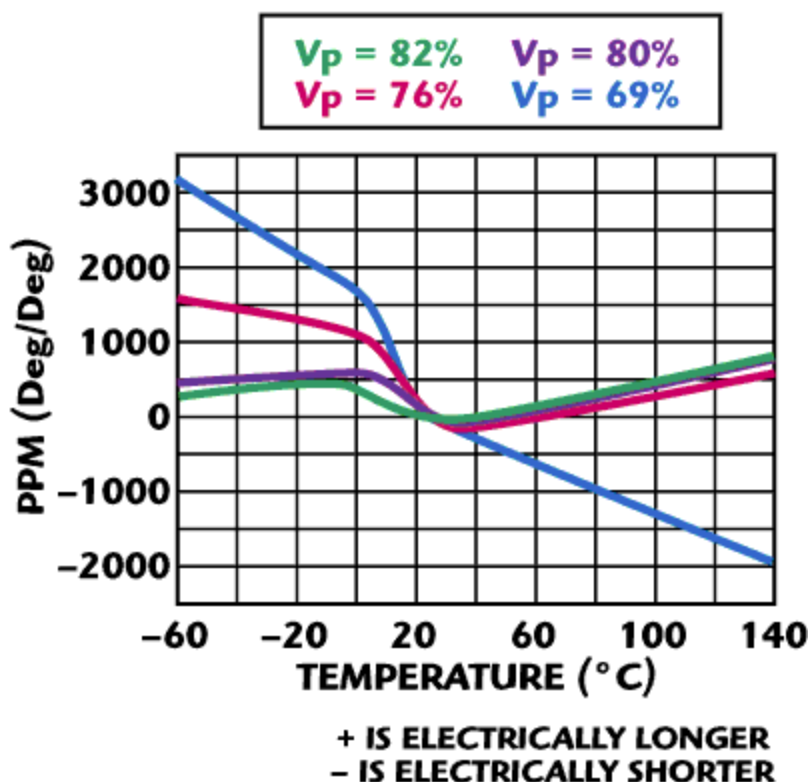


Figure 2 Phase vs. temperature characteristics for representative cable families.

How do we use this data? Suppose two ten-foot assemblies are perfectly matched to each other at room temperature. Now suppose one cable of the pair is used in a 25°C temperature controlled area while the second cable is used in an area where the temperature varies from -55° to $+125^\circ\text{C}$. Using the formulas given above, combined with the phase-temperature changes given in Figure 2, we can determine the electrical length at any temperature.

Consider common RG and semi-rigid cables with solid PTFE dielectric and V_p of 69 percent. At room temperature the phase shift is $95,482^\circ$. At -55°C the length increases 3075 ppm (.003075) or by 294° ; at $+125^\circ\text{C}$ it decreases by 162° . At 30°C , the length decreases by 8.1° . Looking at the situation differently, if we match to a specific phase shift but don't control the temperature, we can have a large phase difference in our cables.

If the dielectric were air-spaced Teflon with V_p of 82 percent, the numbers are quite different. The room temperature phase shift is $80,345^\circ$. At -55°C the length increases by 26° ; at $+125^\circ\text{C}$ it increases by 57° . At 30°C , the length decreases by only 0.8° making thermal control during the phase match operation less critical.

Length of the Cable Assembly

The longer the cable assembly, the more difficult is the matching task. Long cables are difficult to handle and manipulate. They have greater thermal mass and, as illustrated previously, show greater phase changes due to small temperature changes.

Connector Interfaces

It is much easier to phase match cable assemblies when all the cables in the set have the same connectors. That does not mean that an assembly with straight connectors cannot be matched to one with angled connectors; or one with TNC connectors cannot be matched to one with SMA connectors. It just adds to the difficulty and uncertainty of the match. Also, the uncertainty is higher if the assembly is non-insertable; that is, it does not have a plug and jack of the same connector series.

In some applications it is necessary to account for the phase changes that occur during installation. Often the system software does this. It can also be accomplished through the use of phase adjustable connectors attached directly to the cable assembly.

Test Equipment Accuracy

It is highly recommended that a Vector Automatic Network Analyzer be used for the measurement of electrical length. To achieve a high degree of accuracy, the test equipment as well as the cable assemblies must be stabilized in a temperature-controlled room. For best results, do the final phase trimming and ATP testing in the same temperature controlled room. It is also necessary to have phase matched test adapters whenever the cable assembly is non-insertable.

Installation Considerations

It is well known that bending a coaxial cable results in a phase change. To achieve the best match, all cables of a set must be worked on in a standard configuration. They can be coiled on a form, in a “U” or any other convenient shape. However, like all rules there is an exception. When the cables of a matched set are bent into different shapes in their installed condition, test fixtures simulating the installation bends should be used during the matching process.

Matching in Sets

There are two ways of phase matching sets of cables:

- Matched to a standard
- Matched to other cables in the set

Matching to a Standard

The phase standard could consist of either a “Gold” hardware standard or an unchanging software standard, i.e. a known electrical length in degrees at a specific frequency and temperature. Cable assemblies that are phase matched to a gold standard are completely interchangeable. Similarly, cable assemblies that are phase matched to a software standard (known electrical length) are also completely interchangeable. In addition, the use of software standards is more cost effective since they do not require extra material to produce physical standards and they never wear out or degrade with time. With this approach any cable of a set can be replaced without replacing all cables of the set.

Matching as a Set

Cable assemblies matched as a set are only guaranteed to be matched to other cables in the same set. There is no guarantee that the cables in any one set will match those of another set, especially if they are manufactured at different times. This approach results in the lowest cost because cable yields are highest. The drawback is that should any one cable of a set have to be replaced, the entire set may need to be replaced.

Specifying Phase Matched Sets

To produce phase matched sets the manufacturer needs as much of the stated information as the designer can provide. At a minimum, we need to know which cables make up the set, the highest frequency of operation and the desired match. We also need to know if phase standards are required. For critical applications we need to know the bends of the installed configuration so the matching is achieved simulating the installed configuration. This is especially true of long cables where one or more cables might be coiled while others are relatively straight.

Phase Tracking

Phase tracking is primarily influenced by four parameters:

- Consistency
- Preconditioning
- Temperature
- Bends

Consistency

Achieving good phase tracking requires cables that behave alike. Manufacturers carefully select and screen the materials that make up its cables and carefully control the manufacturing processes. Thus, each cable run has characteristics quite close to every other cable run. The variation in the phase-temp characteristic is quite small. Without such careful control, the phase temperature characteristic can vary by ± 200 ppm resulting in significant tracking errors.

Preconditioning

Prior to matching the cables of a phase-matched set, it is necessary to thermally stress relieve them to assure good tracking. For example, assume that the first time a cable assembly is exposed to 125°C its phase shift changes by 10 degrees. The second time this might be reduced to 8 degrees; the third time, 7.5 degrees; the fourth time, 7.2 degrees, etc. Thus, thermal cycling artificially ages or stabilizes the assembly. Manufacturers should ensure phase matched cable assemblies are preconditioned prior to final matching.

Temperature Changes

The overall phase tracking due to temperature changes is dependent upon whether all assemblies in the set are exposed to the same thermal environment. The absolute phase change is dependent primarily upon the velocity of propagation. In general, the less the absolute phase changes, the better the phase tracking over temperature. Thus, higher Vp cables are less sensitive to phase temperature changes and track better. This was shown in the examples mentioned previously.

Bends

The overall phase tracking due to bends is extremely difficult to predict. For static installations, it depends upon the number of bends, the angular arc they encompass and the proximity to other bends. If the installation configuration is known in advance, the manufacturer can adjust for it in the fabrication process. For dynamic installations, the tracking depends upon the similarity of the flexure cycle each cable experiences. Often, bundling the assemblies maintains good phase tracking.

Since the tracking deviation is dependent primarily on the similarity of the installation for each cable in the set, the system designer has some precautions to observe. The best phase tracking is achieved when all cables are installed in a similar manner, are exposed to the same thermal environment and/or are flexed together.

Critical Applications

For critical applications where the ultimate tracking is required, the cables of the phase-matched set should be braided into a bundle and enclosed within a protective sheath. If possible, the sheath should be a thermal blanket that maintains the temperature near 30°C where phase-temperature sensitivity is minimal.

Conclusion

With a little forethought a phase matched set of cables can be specified that will meet most system requirements and not break the budget. Therefore, it is best for the system designer to specify the electrical match parameters to be achieved and let the manufacturer determine how to meet the requirement. Using the physical length as a variable may provide an optimum solution.

Ray Schwartz earned his BSEE, MSEE and PhD EE degrees from Northeastern University. He started his career working at Alford Manufacturing Co. designing slotted lines, impedance plotters (the predecessor of the VNA) and related accessories. He quickly recognized the need for precision connectors and test adapters to permit accurate measurements and concentrated on precision connector interfaces. To this end he participated on both the IEEE precision connector committee and ANSI connector group helping to define and standardize test connector interfaces. After transitioning to Adams-Russell (now CDES M/A-COM) in 1977, he concentrated on the design of high performance coaxial cable assemblies for use in harsh environments as well as the design of cable assemblies specifically intended for use in the test lab. As the Cable Technologist at CDES M/A-COM he now concentrates on unique applications for coaxial cable assemblies.