Operating Principles of Ferrite Circulators and Isolators

Ferrite Circulators are passive non-reciprocal devices used in high frequency applications such as communication systems (radar, cellular base station, etc.) A single junction ferrite circulator can be made with three or more ports. However a single junction three ports circulator is the most popular and cost effective design (compared to single junction with 4 or more ports) and therefore widely used in the industry.

Ferrites are highly resistive ferrimagnetic nonconducting oxides that allow total penetration of electromagnetic fields and exhibit a ferrimagnetic resonance (FMR) phenomenon at high frequencies. Ferrite materials used for circulators usually have low dielectric loss and low magnetic loss at RF and microwave frequencies.

A junction circulator is a 3-port device formed by a symmetrical Y-Junction strip line coupled to a magnetically biased ferrite material. When one of the ports is connected to either an internal or external termination, the device becomes an isolator which isolates the incident and reflected signals. Operation of a junction circulator or isolator is affected by the followings:

Ferrite Region

A ferrite disk and the intersection of 3 transmission lines from the Y-junction is where the actual circulation occurs. A signal entering the circulator generates two counter-rotating waves. Each wave travels at a different velocity so that addition and cancellation occurs at the appropriate ports.

Concept of Circulation and Ferrimagnetic Resonance:

A signal applied to a ferrite disk will generate two equal, circularly polarized counter-rotating waves that will rotate at velocities $\omega+$ and $\omega-$. The velocity of a circularly polarized wave as it propagates through a magnetically biased microwave ferrite material will depend on its direction of rotation. By selecting the proper ferrite material and biasing magnetic field, the phase velocity of the wave traveling in one direction can be made greater than the wave traveling in the opposite direction.

If a signal were applied at Port 1 the two waves will arrive in phase at Port 2 and cancel at Port 3. Maximum power transfer will occur from Port 1 to 2 and minimum power transfer from Port 1 to 3, depending on the direction of the applied magnetic field. Due to the symmetry of the Y-Junction, similar results can be obtained for other port combinations. Externally the circulator directs the signal flow clockwise or counterclockwise, depending on the polarization of the magnetic biasing field.

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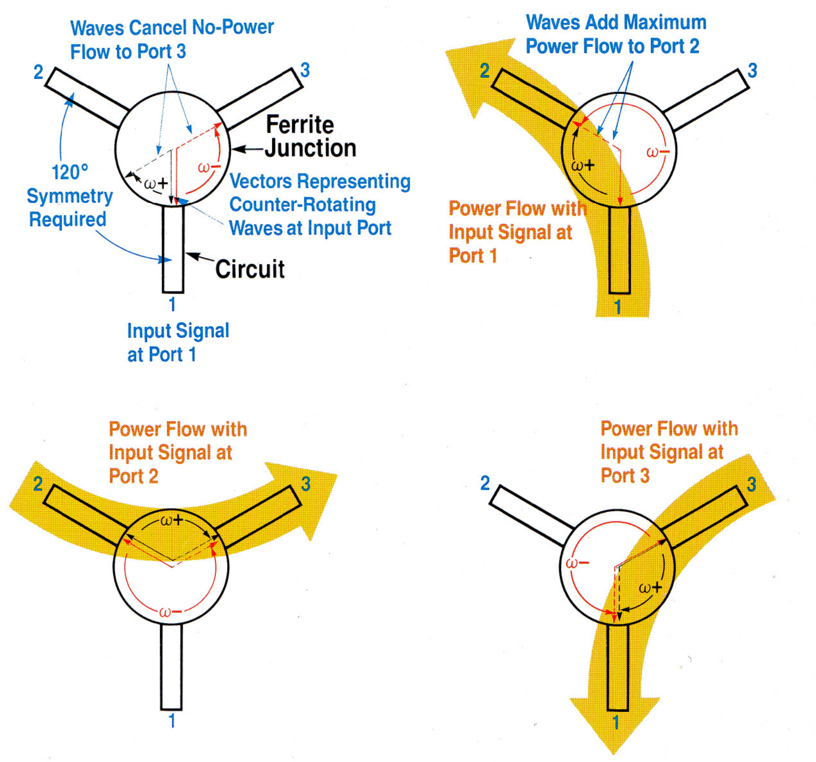

Figure 1 - Power flows when signal applied to different ports of the Y-Junction circuit

When the ferrite material is magnetized, the magnetic moments of the electrons precess at a frequency proportional to the biasing magnetic field. Ferrimagnetic resonance occurs when a rotating RF magnetic field has the same direction and frequency as the precessing electrons in the ferrite material. The maximum coupling of the energy from the RF signal to the ferrite material will occur at ferrimagnetic resonance. If the direction of rotation or the frequency of the RF signal is changed, minimum coupling will occur.

A simplistic analogy can be used to explain these phenomena. It is easier for a person to pass items to an individual riding on a merry-go-round if he is running in the same direction and at the same speed while it is more difficult to pass them if both are moving in opposite directions.

Biasing the junction circulator at ferrimagnetic resonance is not desirable because the circulator would be extremely lossy. High insertion loss can also occur at very low biasing magnetic fields. This low field loss region arises from the fact that the applied magnetic field is not sufficient to fully saturate or align the individual magnetic domains of the ferrite material. Although high loss occurs in both the low field and ferrimagnetic resonance areas, low loss operation can still be obtained in the below and above resonance regions.

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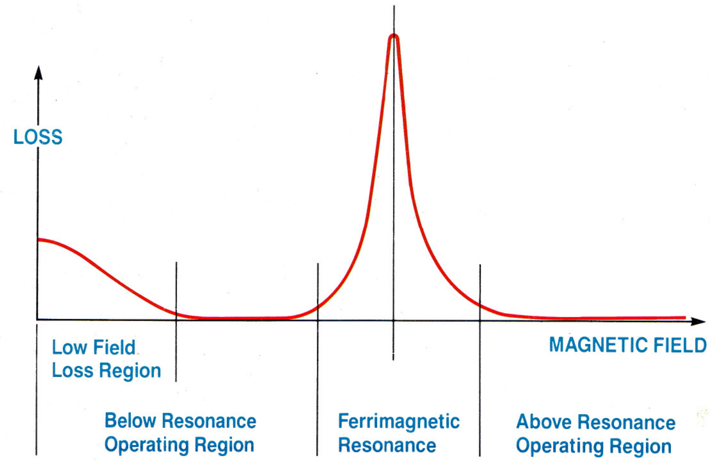

Figure 2 - Ferrite Resonance Curve

Comparison of "Above" and "Below" Resonance Designs:

Operating Frequencies: "Above Resonance" (A/R) circulators and isolators can be designed to operate from 50 MHz to approximately 2.5 GHz. Although operation above this frequency can be achieved, impractical magnetic circuits are required in order to bias the ferrite material. Operation at frequencies below 50 MHz is difficult because the magnetic field the demagnetizing factors of the ferrite geometry do not allow proper biasing of the junction.

"Below resonance" (B/R) circulators and isolators are generally limited to operation above 500MHz. Operation below this frequency is possible but generally more limited in performance. As the frequency is reduced the B/R region of operation diminishes.

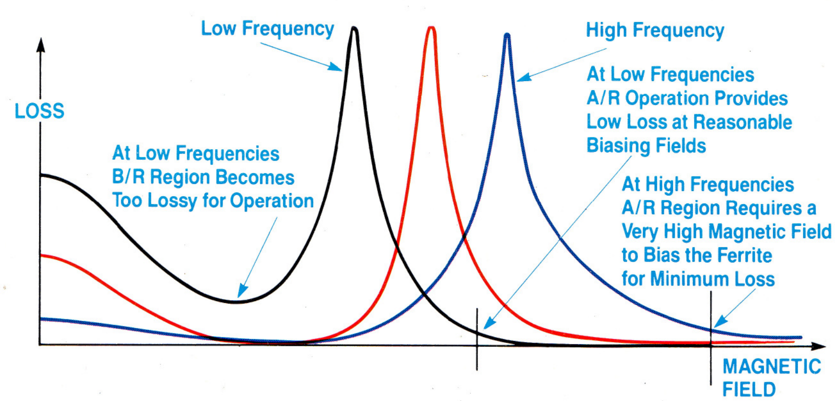

Figure 3 – Comparison of A/R and B/R operations at different frequencies

The lower magnetic field required for operation of the B/R junction is not sufficient to fully saturate the ferrite material, resulting in the low field loss region. The low field loss and ferromagnetic resonance regions merge together, thereby reducing or eliminating entirely the B/R region for ferrite operation. The B/R junction can operate at frequencies to approximately 30 GHz. Operation above this frequency is limited mainly by the strip line geometry. Waveguide circulators can be designed to operate at frequencies greater than 100 GHz.

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Lumped element circulator or isolator designs replace the quarter-wavelength transformer sections with discrete capacitors and inductors to achieve small package sizes in the frequency range of 50 MHz to 1.0 GHz. These devices are temperature sensitive and operate over narrow bandwidths at low power levels.

Bandwidth: B/R junction characteristics allow broad bandwidth operation up to 100%. The A/R junction is generally limited to 40% maximum bandwidth.

Temperature: The A/R circulator or isolator can be temperature compensated using special magnetic materials. The magnetic properties of these materials change with temperature and are used to compensate for the ferrite junction temperature characteristics. Above 1 GHz, operation over a temperature range of -40℃ to +85℃ is common.

The B/R junction is virtually limited to room temperature operation below 1 GHz. The magnetic properties of the ferrite materials available to build circulators or isolators at these frequencies are extremely temperature sensitive. Available materials have Curie temperatures (T_C) less than 100℃. The Curie temperature is defined as the temperature at which the ferrite material's magnetic characteristics are reduced to zero. Circulation of the input signal cannot occur at this temperature. In general, ferrite materials used for the higher operating frequencies have greater temperature stability. Operation above 4 GHz and from -40℃ to +85℃ can be obtained depending on the bandwidth and the level of performance desired. The temperature performance of the B/R and A/R circulators can be improved by the use of temperature compensating material in the magnetic circuit.

Junction Size: The ferrite disk diameter is a function of the effective permeability, dielectric constant, and operating frequency of the ferrite junction. The A/R junction has a greater effective permeability than the B/R junction because of the higher internal magnetic biasing field and ferrite saturation magnetization value. The ferrite disk in the A/R junction will therefore be smaller than the B/R junction for the same operating frequency. For narrow bandwidths in the 1.0 GHz to 2.5 GHz range the A/R junction circulator is usually smaller.

Magnetic Circuit

The magnetic circuit includes "Temp Comp" materials that used to compensate for the reversible changes in magnetic field with temperature changes. Optimization of the magnetic circuit can be done to provide additional magnetic shielding for critical applications where units are mounted in close proximity.

Impedance Transformation

Multiple quarter-wavelength sections of transmission line are commonly used to match the lower impedance of the ferrite disk to the 50 Ohm impedance of the interface. The VSWR and bandwidth sections determine the number of transformer sections required. A typical VSWR specification for a circulator or isolator is a 1.25:1.

For narrow bandwidths (less than 5%) the ferrite junction impedance can be designed to be 50 Ohms. Matching transformers are not required for this type of design which allows a small package size to be obtained. The impedance characteristic is shown below in Figure 4A.

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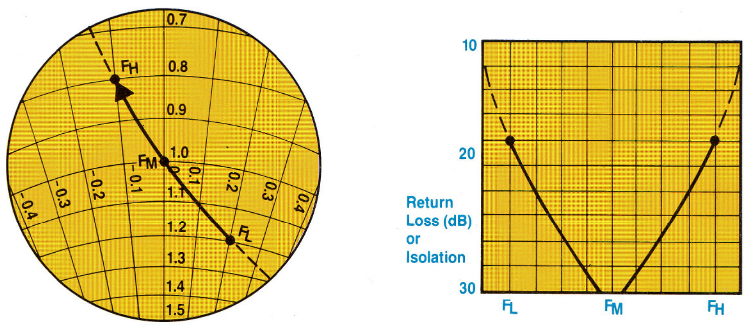

Figure 4A - Impedance characteristics of circulator for narrow bandwidth (Single Tuned Matching)

Moderate bandwidths (less than 40%) can be obtained for both the A/R and B/R junctions by using a single section transformer external to the ferrite disk. The transformer length can be shorted by using high dielectric materials and optimizing the circuit. The single section transformer can also be designed to be included within the ferrite region. Although a more compact size can be obtained, the bandwidth using this technique will be on the order of 25%. The impedance characteristics of the single section design can be seen in Figure 4B.

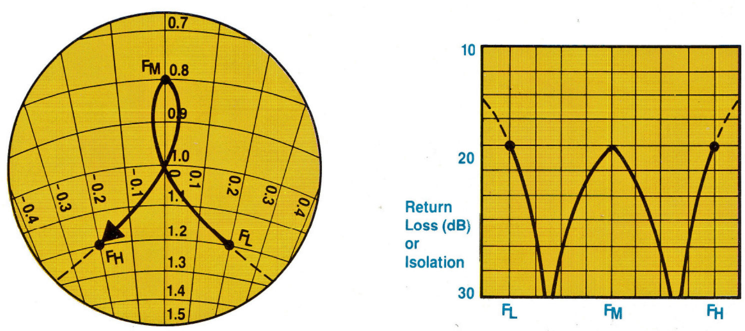

Figure 4B - Impedance characteristics of circulator for moderate bandwidth (Double Tuned Matching)

Bandwidths greater than an octave, can be obtained for the B/R junction, by using two or three external transformer sections. Using more than three transformer sections provides little improvement in performance due to the limitations of the ferrite junction. The A/R ferrite characteristics limit its operation to the previously discussed 40%. The typical two section (Triple Tuned Circuit) transformer impedance characteristics are shown in Figure 4C.

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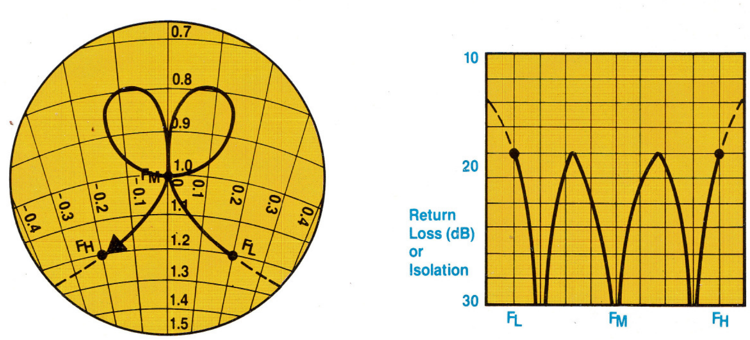

Figure 4C - Impedance characteristics of circulator for broad bandwidth (Triple Tuned Matching)

Transmission Line Geometry

Most common circulator junction is constructed in balanced stripline. Other applications require circulator to be constructed in microstrip. A microstrip circulator consists of a thin film or thick film deposited circuit on a ferrite substrate with metalized ground plane. Magnets on one or both sides of the substrate provide the necessary biasing magnetic field. Microstrip designs are somewhat limited in performance when compared to stripline but they can be easily integrated with other microstrip components.

Interface of Input & Output

Different types of connectors (both removable and non-removable) can be supplied on coaxial circulators and isolators. Connectors such as SMA, Type N and TNC are commonly used. The configuration and performance of some connectors can limit the high frequency electrical performance and the operating bandwidth of circulators and isolators.

Drop-in circulators and isolators use the stripline tabs to mount directly onto a microstrip assembly (PC Board). SMD units interface via a pin or PCB installed at the bottom of the devices. The installation of these circulators and isolators require custom Surface Mount Technology process.

Waveguide circulators & isolators require appropriate waveguide interface for specific operating frequency range. Depends on the applications, a waveguide adapter can be mounted to one of the ports and makes a Coaxial-Waveguide interface.

OPERATING PARAMETERS

INSERTION LOSS:
The ratio of the output signal power to the input signal power expressed in dB, when a signal is applied in the low loss direction to the circulator or isolator.

ISOLATION:
An isolator is a two port device made by internally or externally terminating one port of a circulator. The isolation is the ratio of the signal power applied to the output port to the signal power measured at the input port expressed in dB, when a signal is applied in the high loss direction to the isolator.

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VSWR:
The Voltage Standing Wave Ratio (VSWR) is a measure of how well a load is impedance-matched to a source. VSWR specification can be replaced with Return Loss specification. Return Loss is the difference in power (expressed in dB) between the incident power and the power reflected back by the load due to a mismatch.

To convert VSWR to Return Loss:

$$\text{Return Loss} = -20\log\left[\frac{VSWR-1}{VSWR+1}\right]$$

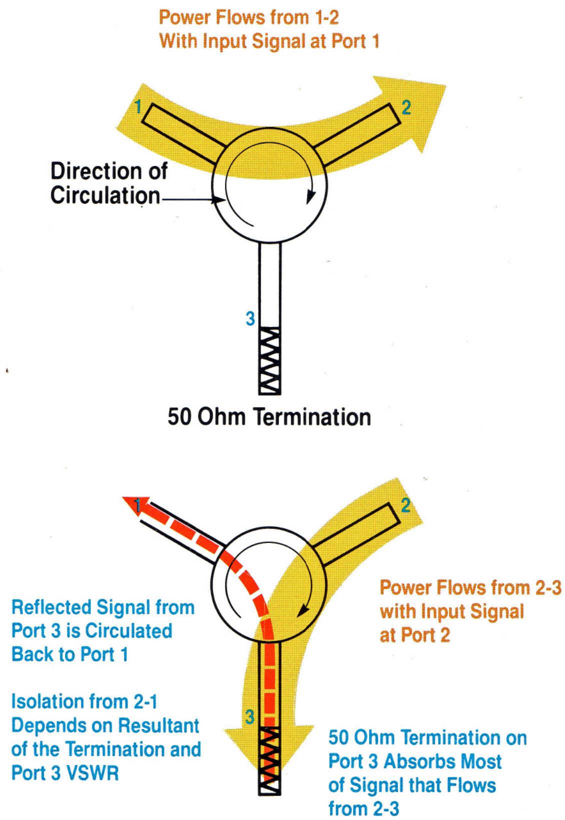

Figure 5 - Connected Port 3 of a circulator with a 50 ohm termination results in an isolator

The parameters isolation, VSWR, and insertion loss are required to specify an isolator whereas a circulator is completely defined by only the VSWR on the three ports and insertion loss. Although a circulator can be made into an isolator by terminating one port, it does not have an intrinsic isolation value. The isolation measured is dependent on the VSWR of both the termination and circulator port.

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Example: A circulator has a measured VSWR of 1.22 for all three ports. If a perfect test termination with a VSWR equal to 1.00 were available to place on Port 3, the resulting isolation from Port 2 to Port 1 would be 20dB. If a test termination with a VSWR equal to 1.05 were placed on Port 3, the resulting isolation from Port 2 to Port 1 would vary between 18.2 and 22.5dB depending on the phasing between the two VSWR's. The resulting isolation value is a function of the VSWR of the test termination and how it phases with the VSWR of the circulator port.

PERCENTAGE BANDWIDTH:
The difference between the high (F_H) and the low (F_L) operating frequencies divided by the center frequency multiplied by 100. This parameter is useful when comparing the relative performance of various circulators or isolators.

$\%BW = 100\% * (F_H - F_L)/F_C$ where $F_C = (F_H + F_L)/2$

TEMPERATURE RANGE:
OPERATING: The temperature range at which a circulator or isolator must meet all specifications.
STORAGE: The temperature range at which a circulator or isolator must survive without permanent degradation in specifications.

PHASE TRACKING:
Phase tracking is a measurement of the variation of the electrical length between the input and the output ports of two or more circulators or isolators. The insertion phase of the A/R circulator or isolator is very sensitive to changes in the magnetic biasing field. This effect can be used to magnetically trim the phase. Some degradation in VSWR or isolation may be required to allow this method of trimming to be used. The insertion phase of the B/R circulator or isolator cannot be easily adjusted.

PHASE LINEARITY:
This parameter is defined as a deviation from a best fit straight line of insertion phase versus frequency. For A/R and B/R circulators or isolators with less than 20% bandwidth the phase linearity will generally be within 2 degrees.

IMPEDANCE CHARACTERISTICS:
This parameter describes both the magnitude and phase of the reflected signal recorded as an impedance plot on a Smith Chart (see Fig. 4a, 4b & 4c). The phase change is proportional to the number of transformer sections used to obtain a given bandwidth. For moderate bandwidths it is possible to restrict the phase change to less than 360 degrees.

PEAK POWER:

Breakdown:
The peak power breakdown value of a circulator or isolator is reduced by an increase in load mismatch, altitude, temperature, or pulse width. A mismatch on the output port will reflect a percentage of the signal back into the circulator or isolator causing a higher internal voltage level which will reduce the power rating of the circulator or isolator. The peak power rating can be increased by filing the internal volume of a circulator or isolator with a high dielectric strength material. Hermetically sealed modules can be used to maintain pressurization for operation at high altitudes.

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Limiting:
Another effect related to the peak power rating of a circulator or isolator is known as the non-linearity or peak power threshold of the circulator or isolator. As the peak power level increases beyond a critical value, the loss versus magnetic field curve will show considerable changes in the region below the main resonance.
The “Above Resonance” region will remain essentially unaffected. The peak power threshold is dependent on the junction geometry, bandwidth, and ferrite material properties. The threshold level can be improved by doping the ferrite material with elements such as holmium, which will cause a slight increase in the insertion loss at low powers.

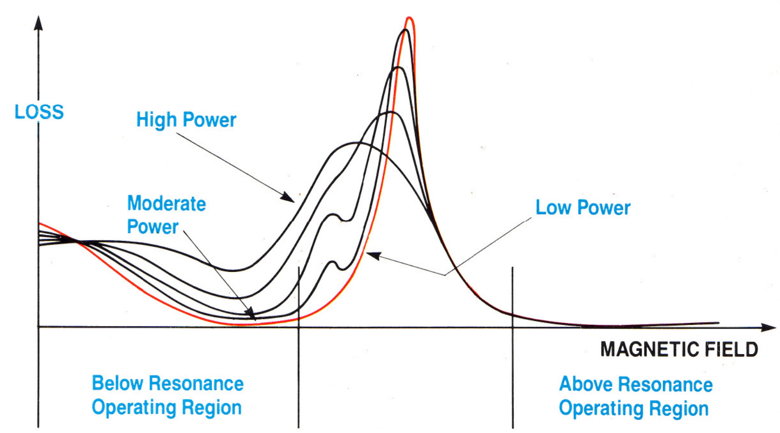

Figure 6 - Peak Power Effects on Resonance Curve

Harmonics:
At high peak power levels the non-linearity of the circulator or isolator generates harmonic and intermodulation products within the ferrite junction. Because of design limitations imposed by other parameters it is difficult to eliminate this effect.

AVERAGE POWER:

The power dissipated in the circulator or isolator is in proportion to the insertion loss. If the average power level is significant, the dissipated power will cause heating of the ferrite junction and degradation in performance.

Conduction, convection or liquid cooling can increase the average power rating of a circulator or isolator. The connector type is also important when the average power is significant. Captured SMA and hermetic seal connectors are limited in power rating because of their internal losses.

The average power rating of a circulator or isolator will also depend on the resultant mismatch at the output port. For example if a signal of 100 Watts average power were applied at the input of a circulator terminated with a 6.00:1 mismatch, 51 watts would be reflected, requiring the circulator to handle 151 watts total.

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ISOLATOR TERMINATION RATING:

The power rating required for the termination of an isolator depends on the mismatch on the output port as shown below:

Mismatch on Output Port	Percent Power Reflected
1.0 (Perfect Match)	0
1.15	0.5
1.20	0.8
1.22	1.0
1.25	1.2
1.30	1.7
1.35	2.2
1.50	4.0
2.0	11.1
6.0	51
Short or Open Circuit	100

RFI LEAKAGE:

RFI leakage values of 30dB or less are easily obtainable in a standard circulator or isolator. Internal plates bonded using conductive epoxy can be used so that values up to 60dB can be obtained. Additional RFI shielding can be provided by utilizing special packaging techniques.

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