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W. J. ALBERSHEIM

2,779,006

SPURIOUS MODE SUPPRESSING WAVE GUIDES

Original Filed Dec. 2, 1949

FIG. 1

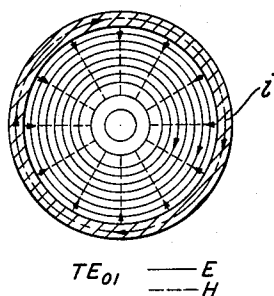


FIG. 2

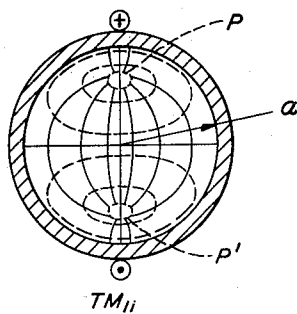


FIG. 3

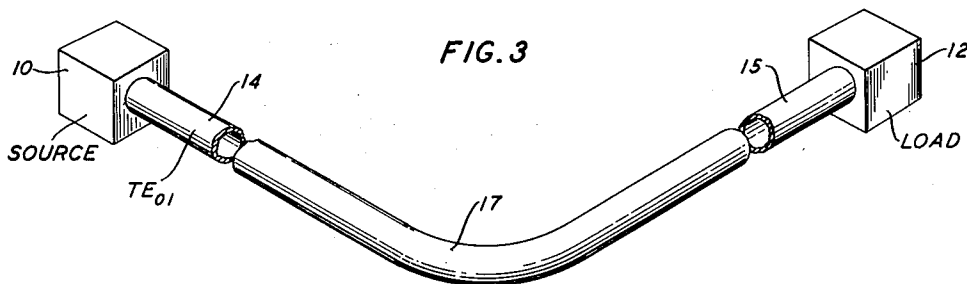


FIG. 4

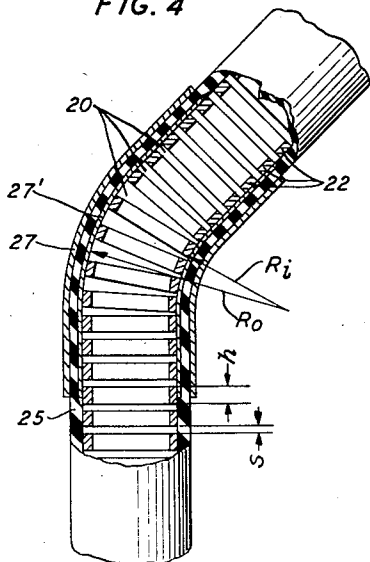


FIG. 4A

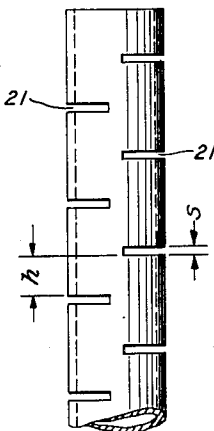
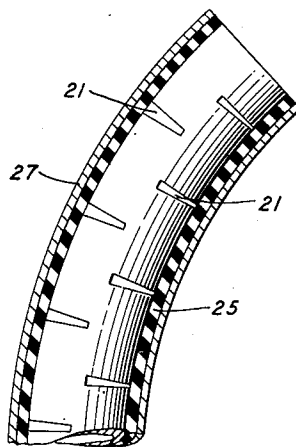


FIG. 4B



INVENTOR
W. J. ALBERSHEIM
BY *H. O. Wright*
ATTORNEY

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SPURIOUS MODE SUPPRESSING WAVE GUIDES

Walter J. Albersheim, Interlaken, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Original application December 2, 1949, Serial No. 130,670. Divided and this application October 10, 1951, Serial No. 250,752

13 Claims. (Cl. 333—98)

This invention relates to the guided transmission of ultra-high frequency electromagnetic waves and, more particularly, to the propagation of waves of the circular electric or TE₀₁ mode through curved bends and elbows in circular wave-guide structures. As used throughout the specification, the term bend will be taken to refer to gradually curved sections of wave guide having large bending radii while the term elbow will be used to refer to relatively sharp curved sections of wave guide having short bending radii.

This application is a division of my copending application Serial No. 130,670, filed December 2, 1949, now Patent 2,649,578 granted August 18, 1953, and entitled "Wave-Guide Elbows."

The propagation of microwave energy in the form of TE₀₁ waves in circular wave guides is ideally suited for the long distance transmission of wide band signals since the attenuation characteristic of this transmission mode, unlike that of all other modes, decreases with increasing frequency. However, one difficulty with this method of transmission is that the TE₀₁ mode is not the dominant mode supported in a circular wave guide, and consequently energy may be lost (by transformation) to other modes also capable of transmission therein. In an ideal wave guide which is perfectly straight, uniform and conducting, the propagation of TE₀₁ waves therethrough is undisturbed, but slight deformations and imperfections in the guide and especially curvature of the wave-guide axis may excite waves of other modes and produce serious losses. These losses are attributed mainly to the fact that the bending of the guide produces a coupling between the desired TE₀₁ and other transmission modes, mainly the TM₁₁ mode.

In his article entitled "Propagation of TE₀₁ Waves in Curved Wave Guides" appearing in the January 1949 issue of the Bell System Technical Journal, vol. 28, No. 1, applicant describes the nature of this mode coupling and likens it to that between traveling alternating-current waves in coupled transmission lines. Each mode capable of transmission in the wave guide is analogous to a separate transmission line. Since the predominant losses in the bends and/or elbows considered herein are due to interaction between the TE₀₁ and TM₁₁ modes, it will be sufficient to consider only two coupled lines; a "primary" line representing the desired or TE₀₁ mode and a "secondary" line representing the undesired or TM₁₁ mode.

In two such lines there exist for each frequency and direction of travel two distinct traveling-wave configurations, from superposition of which all possible current distributions may be built up. In the limiting case when the lines are uncoupled, these configurations consist of a wave in the primary line alone and a wave in the secondary line alone. When the lines are coupled it is not possible to impress a current on one line alone without generating a secondary current in the other line. The two possible wave configurations in the second case are (a) one in which the electromagnetic fields generated by the

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currents in the two lines tend to be in phase and reinforce each other, and (b) one in which the fields tend to be in opposite phases and weaken each other. Due to the greater energy storage, configuration (a) has a slower phase velocity than configuration (b), so that if both configurations coexist, there will be beats between them as they travel along the two lines. Due to the different phase relations between primary and secondary currents in the two configurations, these beats alternately increase and decrease the current in each line in a sinusoidal manner. If at the point of origin, current is made to flow in the primary line only, configurations (a) and (b) will coexist in such amplitude and phase relations that their components cancel each other out in the secondary line at that point; at other points along the lines energy will be transferred in increasing or decreasing amounts into the secondary line so that a sinusoidal current flow in that line will be observed.

The amount of energy transfer between lines per unit length has been shown in applicant's above mentioned Bell System Technical Journal paper to depend upon the coupling discriminant η which is defined as the coupling coefficient k divided by the relative difference in propagation constants, and may be expressed as follows:

$$\eta = \frac{k}{\Gamma_1 - \Gamma_2} \sqrt{\Gamma_1 \Gamma_2} \quad (1)$$

The coupling coefficient k may be expressed broadly in terms of the energy stored in the individual lines 1 and 2 and the energy transferred from one line to the other. Applicant's paper shows that if the coupling discriminant is much smaller than one, only a small fraction of the energy originally flowing in the primary line will be transferred to the secondary line before the energy flow is reversed; if the coupling discriminant is much larger than unity, nearly the entire energy flows back and forth between primary and secondary lines.

For the purpose of further exposition of the present invention the term effective interaction length is introduced. This term may be defined mathematically as the integral of the coupling discriminant η over the entire length of the coupled line section and will therefore indicate the total energy transfer between lines. It should be noted that the coupling coefficient k may vary from positive to negative values (for instance by reversing the polarity of a coupling inductance) and it is therefore possible to make the effective interaction length zero even though the coupling coefficient is finite over nearly the entire coupling length.

Applying the above transmission line analogy to the coupling between the desired TE₀₁ mode and the TM₁₁ mode (or in exceptional cases, other undesired transmission modes) in a wave guide containing intentional or unintentional bends or elbows, it has been shown in applicant's above-mentioned Bell System Technical Journal paper that the coupling coefficient k is proportional to the curvature of the bend or elbow and to the diameter of the wave guide. The relative difference in propagation constants

$$\frac{(\Gamma_1 - \Gamma_2)}{(\sqrt{\Gamma_1 \Gamma_2})}$$

between the TE₀₁ and TM₁₁ modes is very small in a smooth, highly conductive wave guide, and approaches zero in a wave guide of zero resistivity and substantially zero curvature.

From this, it follows that in an ordinary smooth wave-guide bend or elbow, the coupling discriminant η as expressed in Equation 1 supra, tends to be large so that nearly the entire energy of the TE₀₁ mode impressed upon the beginning of the bend may be transferred to the TM₁₁ mode by interference between the two con-

figurations consisting of combinations of "primary" and "secondary" currents, that is, of TE_{01} and TM_{11} components.

Accordingly, it is a primary object of the present invention to provide wave-guide bend and elbow designs for the transmission of TE_{01} circular waves, wherein losses due to curvature of the guide are substantially reduced or eliminated.

Another object of the invention is to provide broad band, low loss bend and elbow designs for the transmission of TE_{01} circular waves in wave guides.

A specific object is to provide circular wave-guide bends and elbows wherein degeneration of the TE_{01} wave into TM_{11} wave power is substantially eliminated.

In furtherance of the objectives of the present invention means are provided for minimizing or canceling the effect of interaction between TE_{01} and other mode waves in the deformations, bends or elbows of circular wave guides. In the designs presented in the present application, this is accomplished by increasing the relative difference in propagation constants of the desired and unwanted mode waves and by attenuating the unwanted modes.

The nature of the present invention and other objects, features and advantages thereof will be apparent from a consideration of the following detailed description, from the appended claims, and from the drawings in which:

Figs. 1 and 2 illustrate the transverse electromagnetic field patterns of the TE_{01} and TM_{11} waves, respectively;

Fig. 3 diagrammatically illustrates a microwave oscillator supplying energy in the form of TE_{01} waves to a load through a circular wave-guide passage including a smoothly curved elbow or bend; and

Figs. 4, 4A and 4B are embodiments of the invention utilizing transverse slots in wave-guide elbows or bends.

Referring to the figures, Figs. 1 and 2 illustrate the distribution of the electric and magnetic fields in transverse sections of a pair of circular wave guides supporting the TE_{01} and TM_{11} transmission modes, respectively. The transverse electric TE_{01} wave illustrated in Fig. 1 is designated as the circular electric type inasmuch as the electric field, shown by the solid lines, consists of circular lines coaxial with the guide and lying transversely thereto without any longitudinal components. The transverse component of the magnetic field, indicated by the dotted lines, forms at various points along the guide a radial pattern. The intensity of the electric field attains a maximum approximately half way between the axis and the surface of the guide and drops to zero at the surface. The current flow associated with the TE_{01} wave is predominantly circular around the periphery of the guide as illustrated in Fig. 1.

The configuration of the transverse magnetic TM_{11} mode shown in Fig. 2 is similar to that of a shielded conductor pair. The magnetic field pattern is entirely transverse without any longitudinal components and is indicated by the dotted lines encircling the respective poles p, p' which, in the case of a plane bend, exhibit an orientation in a plane normal to the plane of the bend. Since the magnetic lines must form closed paths, they tend to spread out near the center of the guide and to crowd close together at the inner surface mostly near the vertical axis of the guide thus inducing a considerable longitudinal conduction current flow in the wall of the guide as shown conventionally in Fig. 2.

In a microwave system for the transmission of TE_{01} waves the inside radius a of the circular pipe guide selected for the propagation of these waves must be greater than the critical or cut-off radius a_c for the TE_{01} mode. The cut-off radius a_c for the TE_{01} mode is equal to $0.61\lambda_0$, where λ_0 is the wavelength in free space of the longest wave (i. e. lowest frequency), in the transmission band of frequencies. In practice a is made greater than a_c and may vary in different systems, from about $1.5\lambda_0$ to $15\lambda_0$, for example. For illustrative purposes, a suitable inner radius for the wave-guide structures described herein can

be about $2a_c$ or $1.21\lambda_0$. Thus, if a hollow-pipe guide five inches in diameter (internal dimension) were selected for transmission of TE_{01} waves, λ_0 , in accordance with the above, would be two inches.

In Fig. 3, there is shown a simple wave-guide installation wherein a variable frequency source 10 of any suitable well-known type supplies microwave energy in the form of TE_{01} waves to a load 12, such as, for example, a microwave repeater or antenna, through a circular wave-guiding passage having a hollow interior. Throughout the greater part of its length, the passage comprises a pair of angularly disposed straight uniform sections of wave guide 14, 15, which are joined by a relatively short curved elbow or bend 17, the design of which may assume any of the forms described hereinafter.

The characteristic transformation of TE_{01} into undesirable TM_{11} wave power is ascribed to the fact that these waves have substantially the same phase constants, i. e., phase velocity and wavelength and, therefore, interact strongly in a manner analogous to coupled transmission lines as set forth hereinabove. In the following embodiments of the invention, the elbows or bends are so treated as to change the phase velocity of the TM_{11} wave relative to the TE_{01} wave to increase the relative difference in propagation constants. In addition, attenuation of the unwanted mode is in certain instances also introduced. This reduces the effective interaction length and coupling discriminant as expressed in Equation 1 and avoids conversion of TE_{01} into TM_{11} wave power.

Fig. 4 illustrates in plan the application of one method of affecting the phase constants of the TM_{11} mode which consists of inserting predominantly reactive effects in the wave-guide elbow or bend in such a manner that the phase constants of the TE and TM modes of the same operating frequency will be substantially different. If the wave-guide bend is cut apart by transversal gaps or slots 20 into ring-shaped sections 22, the slots do not appreciably interfere with the transversal current flow of the TE_{01} wave and, therefore, do not substantially change the configuration, wavelength, or velocity of this mode.

However, the TM_{11} mode has a predominantly longitudinal current flow in the wave-guide walls, and it is seriously affected by the division of the guide into short cylindrical rings. At low frequencies, each slot would be a complete open circuit and suppress all current flow, but at the microwave frequencies, involved in wave-guide propagation, each gap constitutes a large capacitive series reactance which serves to increase the phase velocity of the TM_{11} mode. If the slot width were increased sufficiently to cause the inserted capacitive reactance to exceed the inductive reactance of the remaining metal wall, the TE_{01} mode would not be altered appreciably while spurious transmission modes like the TM_{11} would be suppressed altogether.

In a practical structure, the rings shown in Fig. 4 may be enclosed or embedded in a protective casing 25, which may be a rubber hose, a metal or plastic braid or any other suitable protective covering known to the art. The casing may either be rigid, forming a permanent structure, or pliable, forming a flexible one, as shown in Fig. 4. If the covering is made of a non-conductor or a non-conducting dielectric material, a small fraction of the TE_{01} energy and a large part of the spurious TM_{11} energy may be dissipated laterally by radiation through the ring slots 20 and cause the cross-talk between adjacent wave guides. Radiation losses and cross-talk can be prevented by covering the outer and/or inner surfaces of the dielectric casing 25 with thin metal shielding layers 27, 27' which may be plated, sprayed, dusted, or painted on. Due to skin effect, the currents flowing in the walls of a wave guide are confined near its inner surface, and accordingly the thickness of the shielding layers need not be greater than approximately 0.1 mil. In the presence of the shielding layers, the longitudinal current flow of the TM_{11} mode follows an irregularly raised path which alters

the wave-guide reactance to the undesired mode and affects its phase velocity.

Some of the stray energy reaching the layers 27, 27' is reflected back into the wave guide further affecting the waveguide reactance to the undesired transmission modes. These reflection effects vary with frequency and may exhibit sharp cavity resonance effects at some frequencies. A more uniform modification of the wave-guide reactance may be obtained by using a lossy material in the casing 25, such, for example, as a plastic material in which carbon dust has been dispersed. In this case, only the metallic shielding layer 27, located on the outside of the casing, should be used.

A self-supporting and semirigid structure similar in performance to the ring-type structure of Fig. 4 may be obtained by slotting the wave-guide bend only partially around its circumference, as shown in Figs. 4A and 4B. Even the partial slots 21 interfere sufficiently with the TM₁₁ mode to increase its phase velocity considerably and thus reduce the mode coupling and the resulting transfer of energy to the TM mode.

The guide may be slotted before being bent to form as illustrated in Fig. 4A. In Figs. 4 and 4B, only the curved section of the guide need be slotted. It may not be necessary to employ any form of impedance matching transition into the unslotted straight section of the guide. Fig. 4 is suited for sharp bends or elbows which may be further defined arbitrarily as a bend whose inner radius of curvature R₁ is less than about three-fourths of the outer radius of curvature R₀. In Fig. 4, the distance *h* between slots should preferably be of the order of magnitude of

$$\frac{\lambda_0}{4}$$

or less. The slot width *s* may be on the order of

$$\frac{\lambda_0}{8}$$

or less wide. Where λ_0 , the wavelength in free space of the longest wave in the transmission band, is two inches, by way of a specific example, the distance *h* can be approximately 0.5 inch and *s*, approximately 0.2 inch. In very gradual bends (where the inner radius of curvature is at least three-fourths of the outer radius of curvature), such as those for which Fig. 4B is intended, it is permissible and economical to make the interval *h* greater than

$$\frac{\lambda_0}{4}$$

it may be sufficient to make the slots at intervals corresponding to about one degree of bending, regardless of their separation. For sharper bends or to provide increased flexibility the distance *h* can be made appreciably less than

$$\frac{\lambda_0}{4}$$

without substantially impairing the transmission properties of the structure.

In order to prevent contamination, radiation loss, and cross-talk, and to introduce substantial dissipation of unwanted mode waves, the structure of Fig. 4B may, as indicated, be supplied with the same type of coverings discussed above in connection with Fig. 4.

In Figs. 4, 4A, and 4B, a modification of undesired waves, principally of the TM₁₁ transmission mode, is accomplished by the removal of metal from the wall of the wave-guide bend, thus changing the phase constants of the bend only slightly for TE and very appreciably for TM waves of the same operating frequency.

Viewed from the standpoint of "coupled transmission lines" as discussed in detail above and in my above-men-

tioned paper in the Bell System Technical Journal, the plurality of rings (Fig. 4) or the slotted wave guide (Figs. 4A and 4B) may be said to constitute a practically unbroken conductor for the weak circular currents of the transmission line for the TE₀₁ mode waves, whereas the conductor for the strong longitudinal currents of the transmission line for the TM₁₁ and similar modes includes the capacitive gaps, the casing member 25 and the outer conductive shielding layer 27 of Fig. 4, or a similar casing and shielding member applied to the structure of Figs. 4A and 4B as suggested above. The two lines are coupled mainly through the non-circular energy components in the dielectric inside of the main wave guide caused by the bending of the guide.

In the above-suggested structure, where the casing 25 is made of lossy material, such as a plastic material in which carbon dust has been dispersed, the energy converted to the TM₁₁ mode can be largely dissipated in the casing 25. As is well known to those skilled in the art, if one of two loosely intercoupled transmission lines is highly dissipative while the other is substantially non-dissipative, the highly dissipative line will not absorb large amounts of power from the relatively non-dissipative line. In view of this fact, the structures of the invention appear to offer outstanding advantages as round wave-guide structures for transmitting TE₀₁ mode waves in that they substantially eliminate the most troublesome of the spurious or unwanted modes without the sacrifice of a substantial amount of the power of the TE₀₁ wave being transmitted.

The above-described embodiments are illustrative of the application of the principles of the invention. Numerous and varied other applications can readily be devised by those skilled in the art, without departing from the spirit and scope of said principles.

What is claimed is:

1. A hollow pipe wave guide of circular cross-section for the transmission of high frequency electromagnetic TE₀₁ waves comprising a plurality of conductive ring members coaxially arranged with respect to a common longitudinal axis and spaced along said axis, and a continuous casing or sheath of lossy dielectric material surrounding said members.

2. The wave guide of claim 1, in which said casing or sheath of lossy dielectric material is chosen and arranged to provide flexibility to said wave guide.

3. A high frequency electromagnetic wave guide transmission line comprising a conductive means defining a low-loss dielectric transmission path of circular cross-section, an annular dielectric path surrounding said conductive means throughout the entire length of said transmission line, said dielectric path comprising lossy material uniformly distributed along the length of said transmission line, said low-loss and said lossy dielectric paths being electrically coupled by a plurality of substantially transverse openings in said conductive means, said openings being regularly spaced throughout the length of said transmission line.

4. The transmission line of claim 3, in which said transverse openings extend completely around said first conductive means.

5. A wave guide for the transmission of high frequency electromagnetic TE₀₁ waves comprising a curved hollow conductive pipe of circular cross-section, said pipe including transverse slots spaced regularly along said pipe, said slots extending at least half way around said pipe, alternate slots being positioned on opposite sides of said pipe, and a continuous casing of lossy dielectric material surrounding said pipe.

6. In an electromagnetic wave transmission system, means for producing electromagnetic wave energy in the circular electric mode, means for utilizing said wave energy, and means connecting said utilizing means to said producing means, said connecting means comprising a

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plurality of conductive ring members coaxially arranged with respect to a common longitudinal axis and spaced along said axis, a continuous highly dissipative casing surrounding said members and a layer of conductive material surrounding said highly dissipative casing.

7. The transmission system of claim 6, in which said highly dissipative casing is flexible.

8. A high frequency, electromagnetic wave, waveguide transmission line comprising a first conductive means defining a circularly cylindrical low-loss dielectric transmission path of substantially uniform diameter throughout the length of said transmission line, an annular lossy dielectric path having substantially uniformly distributed loss along said path surrounding said conductive means, said low-loss dielectric path being electrically coupled by a plurality of substantially transverse openings in said first conductive means to said lossy dielectric path at a plurality of spaced points thereon, said openings being regularly spaced along the entire length of said transmission line, and a second conductive means comprising a shielding member surrounding said annular high-loss dielectric transmission path.

9. The transmission line of claim 8, in which said lossy dielectric path and said second conductive means are chosen and arranged to provide flexibility to said transmission line.

10. The transmission line of claim 3 in which said low-loss and said lossy dielectric paths are surrounded by a continuous casing of a protective material.

11. In an electromagnetic wave transmission system, a source of electromagnetic wave energy in the circular electric mode, means for utilizing said wave energy, and transmission means comprising a longitudinal shield connecting said source to said utilizing means, said shield comprising a conductive casing of circular cross-section interrupted by a plurality of substantially transverse discontinuities, each of said discontinuities having a longitudinal dimension substantially less than one half of a wavelength in free space of the longest wave in the transmission band, said discontinuities comprising lossy dielectric material.

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12. In an electromagnetic wave transmission system, a source of electromagnetic wave energy in the circular electric mode, means for utilizing said wave energy, and transmission means comprising a longitudinal shield connecting said utilizing means to said source, said shield comprising a conductive casing of a circular cross-section interrupted by a plurality of discontinuities in the path of longitudinal currents in said shield, each of said discontinuities having a longitudinal dimension substantially less than one half of a wavelength in free space of the longest wave in the transmission band, said discontinuities comprising lossy dielectric material.

13. In an electromagnetic wave transmission system, a source of high frequency electromagnetic TE₀₁ wave energy, means for utilizing said wave energy, and a transmission medium comprising a substantially cylindrical shield connecting said utilizing means to said source, said shield of said transmission medium having a plurality of lossy dielectric regions for longitudinal current components in every wavelength of high frequency wave energy conducted along said medium, said regions being uniformly distributed along the length of said shield, said shield being electrically conductive around the major portion of its circumference for circumferential current components of high frequency wave energy conducted along said medium.

References Cited in the file of this patent

UNITED STATES PATENTS

2,088,749	King	Aug. 3, 1937
2,395,560	Llewellyn	Feb. 26, 1946
2,464,598	Meier	Mar. 15, 1949
2,465,719	Fernsler	Mar. 29, 1949
2,511,896	Bingley	June 20, 1950
2,512,468	Percival	June 20, 1950
2,556,187	Ingalls	June 12, 1951

FOREIGN PATENTS

869,734	France	Nov. 17, 1941
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