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Mathematical Approach of Array Waveguide Grating in Dense Wavelength Division Multiplexing & Demultiplexing

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BSTRACT: This paper improve the mathematical equations of arrayed waveguide grating (AWG) in Dense Wavelength Division Multiplexing and demultiplexing that used to reduce an accumulated crosstalk and optimize the bandwidth for second and third cascade configuration of small AWGs. This paper concerned about the derivation of mathematical equations of the two cascade AWG stages and three stages, these equations improved their mathematical correctness and they are useful for designing the AWGs circuit board.

KEYWORDS: AWG,Dense wavelength division-multiplexing and demultiplexing , Accumulated crosstalk.

I. INTRODUCTION

Several techniques have been used to improve the use of a communication channel, time division multiplexing (TDM), frequency division multiplexing (FDM), and wavelength division multiplexing (WDM) [1] and [2]. With FDM each user is assigned to a certain frequency slot transmitting only with the corresponding carrier, sharing the bandwidth. This technique used in radio transmissions. The FDM could not be used for high channel capacity due to the limitation of using frequency multiplexing at that level to meet this techniques, the dense wavelength division multiplexing (DWDM) is used. This technique opens up new horizons in term of transmission capacity [2].The latest push and vision in networking is the idea of the all optical network where all protocols are carried transparently end to end in optical domain [3]. WDM and DWDM transmit more signals along the communication link with no timing or protocol [4].DWDM systems require lasers with excellent single-mode performance, precise spectral operation according to ITU-T specifications and low-cost fabrication techniques.Optical multiplexers and demultiplexers are essential DWDM components. A multiplexer device allows more than one signal to be combined and then transmitted over a single channel, on the other side the optical signals are retrieved or demultiplexed to their individual signals at the receiver [1].From the standpoint of system design, integrated demultiplexers with low insertion losses are preferred. An interesting approach uses a phased array of optical waveguides that act as a grating. Such gratings are called arrayed waveguide gratings which is better suited for a higher number of channels. AWG is capable of increasing transmission capacity of single optical fiber [4]. The silica-based waveguides are developed AWGs for use as DWDM filters. AWG consists of one input waveguide, several output waveguides and two focusing star couplers slab waveguides also called free propagation region which are connected via an arrayed-waveguides with a constant path length difference between them [6].The crosstalk becomes the major limiting factor in the sensitivity of the array in a DWDM optical communication system. Optical crosstalk arises when the light incident on one channel is coupled to another channel (usually the adjacent one) by reflections or poor fiber-to-photodetector coupling [7]. The crosstalk in AWG is caused by the sidelobes and scattered light of the focused beam in the interface between the second slab waveguide and output waveguide [8]. The cascade connection techniques are used to reduce the crosstalk of conventional AWG filter [9].

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II. RELATED WORK

In [10] the author state that thecrosstalk of nano sized AWG has been a very big challenge in their work, so they proposed novel cascaded waveguide grating filter (CWGF) to decrease the crosstalk of AWG.The authors demonstrated a very low crosstalk SiN-based interleaver with cascaded AWGs, Their measured results show acrosstalk less than -31dB with good suppression to the adjacent and non-adjacent crosstalk in [11]. Reducing total adjacent crosstalk and accumulated total channel crosstalk values ranging from -32 to -25 dB are achieved by cascading a very large channel-count arrayed waveguide grating filter of 1-THz-spaced channels. This large scale AWG is considered as a primary or first stage of cascading, and it functions as a demultiplexer of ten output bandpass this introduces by authors in [12].Another example of cascading two stages of AWGs as a solution to the problem of crosstalk accumulation in large-scale AWG multiplexers and demultiplexers is that of cascaded AWG module resulting in a very low background crosstalk (nonadjacent crosstalk),This technique involves optimizing the bandwidth of the bandpass stage (second stage) AWG by estimating the spectral characteristics of the whole cascaded AWG as a function of its bandwidth and its center wavelength difference. Using a Gaussian spectral profile for assumed the transmittance in linear unit [13]. More related works in[14–15] in which the authors using WDM_phasor for designing 8channel, 16channels, and 32 channels with different channels spacing which conclude that the cascade connection is an attractive methods for improve the AWG accumulated crosstalk.

III. CROSSTALK AND PROPOSED SOLUTION

A crosstalk in conventional AWG has a large-scale limitation. The crosstalk of the AWG based on multiplexer/demultiplexer can be classified in two types' adjacent crosstalk, and nonadjacent crosstalk, shown in equation (1).

$$X_{TOT} = 2X_{adj} + (N-3)X_{nonadj} \qquad (1)$$

Where N is the number of channels of AWG, Xadj and Xnonadj are the crosstalk from the adjacent and nonadjacent channels respectively. For using silica conventional AWG, the level of adjacent crosstalk is about -30dB, and typically -40dB for nonadjacent crosstalk [5-6]. On the other hand the crosstalk can be found from theratio of the transmittanceof two optical channels $\frac{T(\lambda_i)}{T(\lambda_K)}$. In the fiber optics systems the transmittance is the fraction of light transmitted through the system [7].

$$2X_{adj} + (N-3)X_{nonadj} = \sum_{i=K-1,K+1} \frac{T(\lambda_i)}{T(\lambda_K)} + \sum_{i=1,2,\ldots K-2,K+2,\ldots.N-1,N} \frac{T(\lambda_i)}{T(\lambda_K)} \qquad (2)$$

From Figure (1), i can conclude that the worst case of the total crosstalk is -15dB therefore i expected that AWG channels value limited to several hundred. Also the main component that affects the total crosstalk is the nonadjacent crosstalk.

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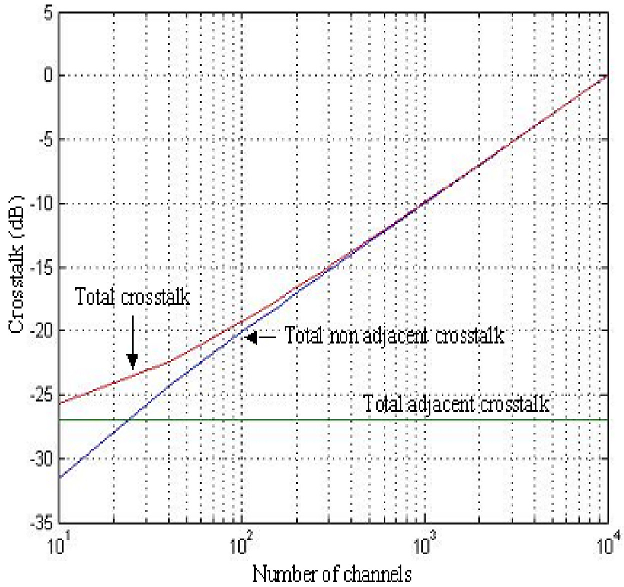

Fig.1 Total crosstalk of conventional AWG compared with the total adjacent crosstalk and total nonadjacent crosstalk.

Crosstalk level required in large-scale AWG can be adjusted by reducing the total nonadjacent crosstalk to be less than -40dB. That means for two stages the nonadjacent crosstalk should be around -80dB for ideal double filtration these value reasonable for 1000 channels [6]. But for the future there is a need of more than two stages of cascaded AWG, to cover the large band ranged from 1300nm up to 1600nm due to the contribution of zero-water-peak fiber. The nonadjacent crosstalk should be around -120dB for the three stages.

IV. PROPOSED AWG CASCADE CONNECTION DESIGN

For meeting the crosstalk requirement of the large –scale AWG, i propose a MUX/DEMUX with small AWG cascade in three stages, configure in figure (3).The first stage is an AWG based on an interleaver filter. That means its outputs are even channels and odd ones in other words the output should be double the input spacing, these technique for making the input to the second stage more relax. The second stage composes of two branches cascading to the first stage using PLC-PLC technique, the same cascading done for stage two to stage three.

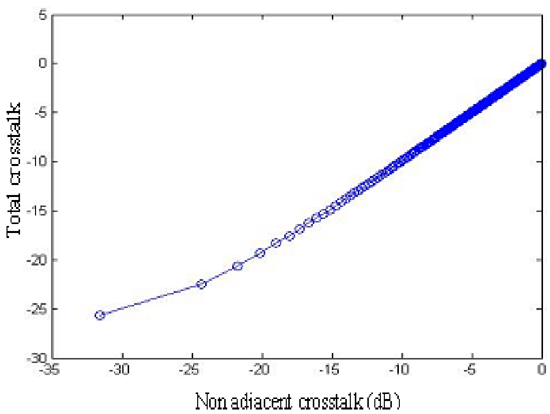

Fig.2 Estimated total crosstalk as a function of its total nonadjacent crosstalk.

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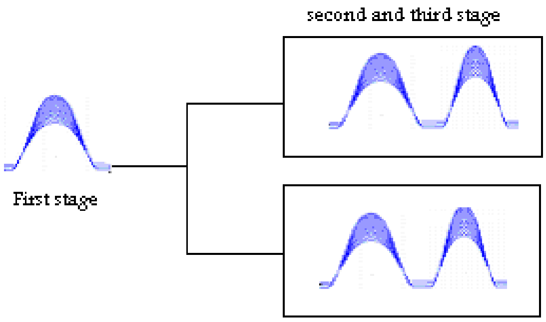

Fig.3 The proposed AWG cascaded connection

The requirements for designing the cascaded AWG, is to minimize the circuit and optimized the bandwidth of the second and the third AWG.

V. BANDWIDTH OPTIMIZATION OF CASCADED AWGS

For design the bandwidth of AWG of the second stage and the third stage, i have to consider that the bandwidth of each stage must be wide but not too broadband; otherwise it will not reduce the nonadjacent crosstalk. I should consider the differences between the center wavelengths of the first AWG and the AWGs of the two cascaded stages, and optimize the bandwidth to absorb the center wavelength differences.

The optimization of the bandwidth of the two cascaded stages can be done by estimated of the spectral characteristics of the cascaded AWG as a function of the bandwidth, and the center wavelength differences due to the following calculations. I assumed the transmittance in linear units $T_1(\lambda)$ for first stage AWG, which has a Gaussian spectral (4) where λ, λ_1 , and σ_1 are the wavelength, the ith channel wavelength, and the bandwidth respectively, the second stage center at channel i = k. the lower limit of the spectrum is Xnonadj,1 this means the first stage nonadjacent crosstalk is Xnonadj,1.I set σ_1 so that the first stage AWG adjacent crosstalk is Xadj,1, in which

$$\sigma_1 = \Delta\lambda\sqrt{-In(Xadj,1)} \qquad (3)$$

Where $\Delta\lambda$ is channel spacing.

$$T_1(\lambda) = \exp\left[-\left(\frac{\lambda-\lambda_K}{\sigma_1}\right)^2\right] for$$
$$|\lambda-\lambda_K| \le \sigma_1\sqrt{-In(Xnonadj,1)}$$
$$T_1(\lambda) = X_{nonadj,1}\ for$$
$$|\lambda-\lambda_K| \rangle \sigma_1\sqrt{-In(X_{nonadj,1})} \qquad (4)$$

I assumed the transmittance $T_2(\lambda)$ and $T_3(\lambda)$ for the second, and the third stages. Where σ_2 and σ_3 are the bandwidths of stage number two and three of proposed design respectively and $\partial_2\lambda, \partial_3\lambda$ are the center wavelength differences from the channel wavelength(λ_K).

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$$T_2(\lambda)=\exp\left[-\left(\frac{\lambda-\lambda_K-\partial_2\lambda}{\sigma_2}\right)^2\right] for$$
$$|\lambda-\lambda_K|\le\sigma_2\sqrt{-In(X_{nonadj,2})} \qquad (5)$$
$$T_2(\lambda)=X_{nonadj,2}\ for|\lambda-\lambda_K|\rangle\sigma_2\sqrt{-In(X_{nonadj,2})}$$

$$T_3(\lambda)=\exp\left[-\left(\frac{\lambda-\lambda_K-\partial_2\lambda-\partial_3\lambda}{\sigma 3}\right)^2\right] for$$
$$|\lambda-\lambda_K|\le\sigma_3\sqrt{-In(X_{nonadj,3})} \qquad (6)$$
$$T3(\lambda)=X_{nonadj,3}\ for|\lambda-\lambda_K|\rangle\sigma_3\sqrt{-In(X_{nonadj,3})}$$

Calculated the product of the transmittance of the two and the three AWGs to estimate the cascaded transmittance T(λ_C) and the spectral characteristics AWG, also calculated σ_C which is the bandwidth of these cascaded AWG as an equation (7) for two stages cascaded and also an equations number (8) and (9) for the three AWGs cascaded.

$$T_c(\lambda)=t_1(\lambda).t_2(\lambda)$$

$$T_c(\lambda)=T_1(\lambda).T_2(\lambda)=\exp\left[-\left(\frac{\lambda-\lambda_K-\left(\sigma_c/\sigma_2\right)^2\delta\lambda}{\sigma_c}\right)^2-\left(\frac{\sigma_c\delta\lambda}{\sigma_1\sigma_2}\right)^2\right]$$
$$for|\lambda-\lambda_K|\le\sigma_1\sqrt{-Ln(X_{NAdj,1})}$$
$$T_c(\lambda)=T_1(\lambda).T_2(\lambda)=X_{NAdj,1}\exp\left[-\left(\frac{\lambda-\lambda_K-\delta\lambda}{\sigma_2}\right)^2\right]$$
$$for\sigma_1\sqrt{-Ln(X_{NAdj,1})}\langle|\lambda-\lambda_K|\le\sigma\sqrt{-Ln(X_{NAdj,2})} \qquad (7)$$
$$T_c(\lambda)=T_1(\lambda).T_2(\lambda)=X_{NAdj,1}.X_{NAdj,2}$$
$$for|\lambda-\lambda_K|\rangle\sigma_2\sqrt{-Ln(X_{NAdj,2})}$$

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Vol. 3, Issue 11, November 2015

$$T_c(\lambda) = t_1(\lambda).t_2(\lambda).t3(\lambda)$$

$$T_c(\lambda) = \exp\left[-\left(\left(\frac{\lambda-\lambda_K}{\sigma_1}\right)^2 + \left(\frac{\lambda-\lambda_K-\partial_2\lambda}{\sigma_2}\right)^2 + \left(\frac{\lambda-\lambda_K-\partial_2\lambda-\partial_3\lambda}{\sigma_3}\right)^2\right)\right]$$

$$for\left|\lambda-\lambda_K\right| \le \sigma_1\sqrt{-In\left(X_{nonadj,1}\right)}$$

$$T_c(\lambda) = X_{nonadj,1}\exp\left[-\left(\left(\frac{\lambda-\lambda_K-\partial_2\lambda}{\sigma_2}\right)^2 + \left(\frac{\lambda-\lambda_K-\partial_2\lambda-\partial_3\lambda}{\sigma_3}\right)^2\right)\right] \quad (8)$$

$$for\sigma_1\sqrt{-In\left(X_{nonadj,1}\right)}\langle\left|\lambda-\lambda_K\right| \le \sigma_2\sqrt{-In\left(X_{nonadj,2}\right)}$$

$$T_c(\lambda) = X_{nonadj,1}X_{nonadj,2}\exp\left[-\left(\frac{\lambda-\lambda_K-\partial_2\lambda-\partial_3\lambda}{\sigma_3}\right)^2\right]$$

$$for\sigma_2\sqrt{-In\left(X_{nonadj,1}\right)}\langle\left|\lambda-\lambda_K\right| \le \sigma_3\sqrt{-In\left(X_{nonadj,3}\right)}$$

$$T_c(\lambda) = X_{nonadj,1}\times X_{nonadj,2}\times X_{nonadj,3}$$

$$for\left|\lambda-\lambda_K\right|\rangle\sigma_3\sqrt{-In\left(X_{nonadj,3}\right)}$$

$$\sigma_c = \frac{\sigma_1\sigma_2\sigma_3}{\sqrt{\sigma^2{}_1\sigma^2{}_2+\sigma^2{}_1\sigma^2{}_3+\sigma^2{}_2\sigma^2{}_3}} \quad (9)$$

VI. 2-STAGE AWG EQUATION DERIVATION

$$t_c(\lambda) = t_1(\lambda).t_2(\lambda) = \exp\left[-\left(\frac{\lambda-\lambda_K-\left({\sigma_c}/{\sigma_2}\right)^2\delta\lambda}{\sigma_c}\right)^2 - \left(\frac{\sigma_c\delta\lambda}{\sigma_1\sigma_2}\right)^2\right] \quad (7)$$

But the original relationship is:

$$t_c(\lambda) = t_1(\lambda).t_2(\lambda) = \exp[-\left(\frac{\lambda-\lambda_k}{\sigma_1}\right)^2]\exp[-\left(\frac{\lambda-\lambda_k-\delta\lambda}{\sigma_2}\right)^2] \quad (10)$$

In the following the two equations (7) and (10) will have their exponents expanded and manipulated in the hope that the two equations agree:Now for equation (10); its exponent is multiplied by $\left(\frac{\sigma_c}{\sigma_c}\right)^2$ to yield that:

$$t_c(\lambda) = \exp\left[-\left(\frac{\frac{\sigma_c{}^2}{\sigma_1{}^2}(\lambda-\lambda_K)^2 + \frac{\sigma_c{}^2}{\sigma_2{}^2}(\lambda-\lambda_k-\delta\lambda)^2}{\sigma_c{}^2}\right)\right] \quad (11)$$

Now expanding the squared brackets of (11)

$$t_c(\lambda) = xp\left[-\left(\frac{[\frac{\sigma_c{}^2}{\sigma_1{}^2}(\lambda^2+\lambda^2{}_K-2\lambda\lambda_k)]+\frac{\sigma_c{}^2}{\sigma_2{}^2}[(\lambda^2+\lambda^2{}_k+\delta\lambda^2-2\lambda\lambda_k-2\lambda\delta\lambda+2\lambda_k\delta\lambda)]}{\sigma_c{}^2}\right)\right] \quad (12)$$

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Vol. 3, Issue 11, November 2015

Rearranging(12)

$$t_c(\lambda)=\exp\left[-\left(\frac{[(\frac{\sigma_c^{\ 2}}{\sigma_1^{\ 2}}+\frac{\sigma_c^{\ 2}}{\sigma_2^{\ 2}})(\lambda^2+\lambda^2{}_K-2\lambda\lambda_k)]+\frac{\sigma_c^{\ 2}}{\sigma_2^{\ 2}}[(\delta\lambda^2-2\lambda\delta\lambda+2\lambda_k\delta\lambda)]}{\sigma_c^{\ 2}}\right)\right] \qquad (13)$$

Then: $\frac{\sigma_c^{\ 2}}{\sigma_1^{\ 2}}+\frac{\sigma_c^{\ 2}}{\sigma_2^{\ 2}}=1$.Therefore equation number (13) will be:

$$t_c(\lambda)=\exp\left[-\left(\frac{[(\lambda^2+\lambda^2{}_K-2\lambda\lambda_k)]+\frac{\sigma_c^{\ 2}}{\sigma_2^{\ 2}}[(\delta\lambda^2-2\lambda\delta\lambda+2\lambda_k\delta\lambda)]}{\sigma_c^{\ 2}}\right)\right] \qquad (14)$$

Now is the turn for equation (7) exponential to be expanded as:

$$t_c(\lambda)=\exp\left[-\left(\frac{(\lambda^2+\lambda^2{}_K+\left(\frac{\sigma_c}{\sigma_2}\right)^4\delta\lambda^2-2\lambda\lambda_k-2\lambda\left(\frac{\sigma_c}{\sigma_2}\right)^2\delta\lambda+2\lambda_k\left(\frac{\sigma_c}{\sigma_2}\right)^2}{\sigma_c^{\ 2}}-\left(\frac{\sigma_c\delta\lambda}{\sigma_1\sigma_2}\right)^2\right)\right] \qquad (15)$$

Then compare (13) and (14) for agreement,it could be noticed that the two equations agree directly for all terms one for one except that the disagreement is in that:

1- Equation(13) has the coming term: $\left[\left(\frac{\frac{\sigma_c^{\ 2}}{\sigma_2^{\ 2}}[(\delta\lambda^2-2\lambda\delta\lambda+2\lambda_k\delta\lambda)]}{\sigma_c^{\ 2}}\right)\right]$ (16)

2- Also equation(14) has this term: $\frac{(\frac{\sigma_c}{\sigma_2})^4\delta\lambda^2}{\sigma^2{}_c}+(\frac{\sigma_c\delta\lambda}{\sigma_1\sigma_2})^2$, then take coefficient ones:

$$\frac{(\frac{\sigma_c}{\sigma_2})^4(1+\frac{\sigma_2^{\ 2}}{\sigma_1^{\ 2}})}{\sigma^2{}_c}=\frac{(\frac{\sigma_c}{\sigma_2})^4(\frac{\sigma_1^{\ 2}+\sigma_2^{\ 2}}{\sigma_1^{\ 2}})}{\sigma^2{}_c}=\frac{\frac{\sigma_c^{\ 4}}{\sigma_2^{\ 2}}(\frac{\sigma_1^{\ 2}+\sigma_2^{\ 2}}{\sigma_1^{\ 2}\sigma_2^{\ 2}})}{\sigma^2{}_c}=(\frac{\sigma_c}{\sigma_2})^2\frac{1}{\sigma_c^{\ 2}} \qquad (17)$$

Same coefficient obtained as in equation (15).From the relationships between channel spacing (Δλ), channel bandwidth (σ1), and channel adjacent crosstalk (xadj,1). Obtain this formula: $t_1(\lambda)=\exp-\left(\frac{\lambda-\lambda_k}{\sigma_1}\right)^2$ then Considering channel k

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International Journal of Innovative Research in Computer and Communication Engineering

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Vol. 3, Issue 11, November 2015

be (λk) then at:λk+1 with Δλ = λk+1 - λk = channel spacing, then: t1(λ) = Xadj,1 = $\exp -\left(\frac{\Delta\lambda}{\sigma_1}\right)^2$, Therefore ln Xadj,1 = $-\left(\frac{\Delta\lambda}{\sigma_1}\right)^2$, Δλ = σ1 $\sqrt{-\ln X_{adj,1}}$ and so:

σ1 = Δλ / $\sqrt{-\ln X_{adj,1}}$.

VII.THREE STAGEBANDWIDTHDERIVATION

$$\sigma_c = \frac{\sigma_1\sigma_2}{\sqrt{\sigma_1^{\ 2} + \sigma_2^{\ 2}}} \qquad (18)$$

This relation for the band width of 2-stage AWG cascaded:Where σ_1 for main AWG, and σ_2 for bandpass AWG.Taking this relationship (18) as it is, then with the main AWG and first bandpass AWG together as the new main AWG and with σ_3 being the bandwidth of the second bandpass AWG with σ_d being the bandwidth of the three AWGs in cascade $\sigma_d = \frac{\sigma_c\sigma_3}{\sqrt{\sigma_c^{\ 2} + \sigma_3^{\ 2}}}$ Substituting for σ_c from (18) then:

$$\sigma_d = \left(\frac{\sigma_1\sigma_2}{\sqrt{\sigma_1^{\ 2} + \sigma_2^{\ 2}}}\right)\left(\frac{\sigma_3}{\sqrt{\left(\frac{\sigma_1\sigma_2}{\sqrt{\sigma_1^{\ 2} + \sigma_2^{\ 2}}}\right)^2 + \sigma_3^{\ 2}}}\right) = \frac{\sigma_1\sigma_2\sigma_3}{\sqrt{(\sigma_1\sigma_2)^2 + (\sigma_1\sigma_3)^2 + (\sigma_2\sigma_3)^2}} \quad (19)$$

Which agree with equation (9).

VIII. CONCLUSION

In summary i have investigated the cascading connection for AWGs. I found that cascaded connection reduces the crosstalk, and optimizes the bandwidth (WB) also i design three stages of AWG cascaded according to the mathematical equations, for enhance the crosstalk by controlling its nonadjacent crosstalk.

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